Investigating intervention strategies for the management of diabetes in South Africa: A system dynamics approach

by

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Declaration

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Abstract

The increasing prevalence of diabetes mellitus in the world is a widespread concern. According to predictions by the International Diabetes Federation, the prevalence of diabetes is expected to increase globally from 415 million in 2015 to 642 million by 2040. While improvement has been made in the epidemiology and management of diabetes in the developed world, the same advances have not been made in South Africa. Similarly to the rest of the world, South Africa is experiencing an increasing prevalence of diabetes, in addition to the highest global prevalence of HIV and Tuberculosis. With more chronically-ill patients, public primary health care facilities are under significant strain to dedicate sufficient resources to assist all patients. This, in turn, minimises the available time allocated to other aspects of primary health care, which includes intervention strategies such as screening and prevention through education. In addition, while the private and public sector both receive a similar share of the GDP for health care, the private health care sector only services a fraction of the population. This inequality between the private and public health sectors proves to be significant challenge that hinders the effective management of diabetes in the public health care system. Furthermore, the prevention and treatment of diabetes is a complex process which requires consistent and methodological care to prevent the onset or progress of the disease. Despite national diabetic policy implementation in 2014, the prevalence of type 2 diabetes has, however, steadily increased from the 4.5% in 2010 to 7% in 2017. In addition, the proportion of all diabetic-related deaths in South Africa has increased from 5.1% in 2014 to 5.5% in 2017. This increase in the prevalence of type 2 diabetes, along with the increased diabetes-related mortality, raises questions relating to the effectiveness of existing diabetes interventions in South African diabetic policy.

The primary research aim of this thesis is, therefore, to investigate existing intervention strategies for policy formulation so as to more effectively manage diabetes within South Africa. Due to the complex nature and non-linear interactions that exist within the diabetic health care system in South Africa, and through the analysis of various modelling approaches, system dynamics modelling was selected as an appropriate analysis method to evaluate diabetic policy interventions and gain insight the causal relationship within this system. Twelve dynamic hypotheses are proposed in the form of a causal loop diagram which is used in the development of a system dynamics model. Using the system dynamics methodology, the dynamics of the (i) non diabetic, (ii) undiagnosed and diagnosed prediabetic, (iii) undiagnosed and diagnosed diabetic, and (iv) undiagnosed and diagnosed diabetic with complications populations are modelled using the *Vensim DSS* software. Policy intervention scenarios are then developed so as to determine the effect of various policy interventions on the total diabetic death rate per year. These scenarios included changing the resource allocation of (i) the health care professional to patient ratio, (ii) self-management education, (iii) lifestyle education, (iv) screening interventions and (v) the availability of medical resources.

Using the scenario results, policy considerations are presented so as to provide insight into the complex and dynamic diabetic health care system, as well as to highlight effective causal relationships. It is shown that through the implementation of two interventions, powerful causal relationships can be established between the health care professional to patient ratio and self-management education interventions, as well as between the health care professional to patient ratio and availability of medical resources interventions. The most significant causal relationship is, however, observed between these three aforementioned interventions — the health care professional to patient ratio, self-management education and availability of medical resources interventions. Although the lifestyle education intervention is shown to reduce the total diabetic deaths per year, no strong relationship was identified in combination with other interventions. The lifestyle education intervention, however, proves to be an effective supportive intervention to already powerful intervention combinations. Finally, although the screening intervention was proven to be the most effective intervention in reducing the undiagnosed diabetic deaths per year, the impact of the screening intervention on the undiagnosed diabetic deaths per year is shown to be significantly less than the impact of the other interventions on the diagnosed diabetic deaths per year.

Uittreksel

Die wêreldwye toename in die voorkoms van diabetes mellitus is 'n bron van kommer. In 2015 was 415 miljoen mense wêreldwyd met die siekte gediagnoseer, die Internasionale Diabetes Federasie voorspel dat di getal teen 2040 na 642 miljoen sal toeneem. Alhoewel verbeteringe in die epidemiologie en bestuur van diabetes reeds in ontwikkelde lande gemaak is, is dieselfde vooruitgang nog nie in Suid-Afrika gemaak nie. Ooreenkomstig met die res van die wêreld, ervaar Suid-Afrika 'n toenemende voorkoms van diabetes, tesame met die hoogste voorkoms van MIV en tuberkulose wêreldwyd. Die toename in pasiënte wat chronies siek is, plaas openbare primêre gesondheidsorgfasiliteite onder toenemende druk om, binne die beperkte hulpbronbeskikbaarheid pasiënte te help. Dit verminder op die beurt die hulpbronne wat gewy kan word aan ander aspekte van primêre gesondheidsorg, b.v. intervensie-strategieë soos voorkomende opleiding. Boonop ontvang die private- en openbare sektor 'n soortgelyke deel van die BBP vir gesondheidsorg, maar die private gesondheidsorgsektor diens slegs 'n fraksie van die bevolking. Hierdie ongelykheid tussen die privaat- en openbare gesondheidsektore blyk 'n groot uitdaging te wees wat die effektiewe bestuur van diabetes in die openbare gesondheidsorgstelsel belemmer. Eweneens is die voorkoming en behandeling van diabetes 'n ingewikkelde proses wat deurlopende en metodologiese sorg vereis om die aanvang of vordering van die siekte te voorkom. Ten spyte van die implementering van 'n nasionale diabetiese beleid in 2014, het die voorkoms van tipe 2-diabetes steeds toegeneem van die 4.5% in 2010 tot 7% in 2017. Daarbenewens het die persentasie van alle sterftes wat verband hou met diabeties in Suid-Afrika toegeneem van 5.1% in 2014 tot 5.5% in 2017. Hierdie toename in die voorkoms van tipe 2-diabetes, tesame met die verhoogde diabetesverwante sterftes, laat vrae ontstaan aangaande die doeltreffendheid van bestaande diabetesintervensies in die Suid-Afrikaanse diabetiese beleid.

Die primêre navorsingsdoel van hierdie tesis is dus om bestaande intervensiestrategieë vir beleidsformulering te ondersoek ten einde diabetes in Suid-Afrika meer effektief te bestuur. Vanweë die ingewikkelde aard van die gesondheidsorgstelsel sowel as die nie-lineêre aard van interaksies binne die stelsel, is stelseldinamika gekies as 'n toepaslike modeleringsbenadering om diabetiese-beleidsintervensies te evalueer ten einde insig te bekom oor die oorsaaklike verband binne hierdie stelsel. Twaalf dinamiese hipoteses word voorgestel in die vorm van 'n oorsaaklike lusdiagram wat gebruik word in die ontwikkeling van 'n stelseldinamikamodel. Die *Vensim DSS* sagtewarepaketword gebruik om die dinamika van die volgende groepe te modelleer (i) nie-diabetiese bevolking, (ii) ongediagnoseerde en gediagnoseerde prediabetiese bevolking, (iii) ongediagnoseerde en gediagnoseerde diabetiese bevolking, en (iv) ongediagnoseerde en gediagnoseerde diabetiese bevolking wat ook komplikasies opgedoen het . Die effek van verskillende beleidsintervensies op die totale jaarlikse diabetiese-sterftesyfer word dan bepaal. Hierdie scenario's het die verandering van die hulpbrontoekennings aan die volgende intervensies ingesluit (i) die gesondheidsorgpersoon tot pasiëntverhouding, (ii) selfbestuuronderrig, (iii) lewenstylonderrig, (iv) keurings intervensies en (v) die beskikbaarheid van mediese hulpbronne.

Die scenario-resultate word ontleed om noemenswaardige oorsaaklike verhoudings uit te lig,

en hoëvlak beleidsoorwegings word na gelang hiervan voorgestel. Die werkverrigting van veral twee stelle intervensies is opmerklik, naamlik: (i) die kombinasie van die gesondheidsorgpersoon tot pasiënt-verhouding en selfbestuur-opvoedingsintervensies; en (ii) die kombinasie van die gesondheidsorgpersoon tot pasiënt verhouding en die beskikbaarheid van mediese hulpbronne-intervensies. Die belangrikste oorsaaklike verband word egter tussen hierdie drie bogenoemde intervensies waargeneem — die gesondheidsorgverhouding tot pasiëntverhouding, selfbestuu onderrig en beskikbaarheid van mediese hulpbronne. Alhoewel daar getoon word dat intervensie wat op lewenstylonderwys fokus die totale sterftes per diabeet per jaar verminder, blyk hierdie intervensie nie in kombinasie met enige van die ander vier intervensies n kragtige uitwerking te hê nie. Nietemin is die intervensie vir lewenstylonderwys 'n effektiewe ondersteunende intervensie. Ten slotte, alhoewel dit bewys is dat die keuringsintervensie die doeltreffendste intervensie was om die ongediagnoseerde diabetiese sterftes per jaar te verlaag, is die impak van die keuringsintervensie op die ongediagnoseerde diabetiese sterftes per jaar beduidend minder as die impak van die ander intervensies op die diagnose van diabetiese sterftes per jaar.

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List of Acronyms

2-h PG	Two-hour Plasma Glucose
ADA	American Diabetes Association
AMR	Availability of Medical Resources
CLD	Causal Loop Diagram
CVD	Cardiovascular Disease
DLECA	Diabetes Lifestyle Education Collaboration and Action
DMR	Decision-Making Rule
FPG	Fasting Plasma Glucose
HCPP	Health Care Professional to Patient ratio
IDF	International Diabetes Federation
IFG	Impaired Fasting Glucose
IGT	Impaired Glucose Tolerance
LADA	Latent Autoimmune Diabetes of Adulthood
MODY	Maturity Onset Diabetes of the Young
NCD	Non-Communicable Disease
OGTT	Oral Glucose Tolerance Test
LEI	Lifestyle Education Intervention
PHC	Primary Health Care
SEMDSA	Society for Endocrinology, Metabolism and Diabetes of South Africa
SI	Screening Intervention
SMEI	Self Management Education Intervention
SDG	Sustainable Development Goal
SVS	Stock Visibility Solution
WHO	World Health Organization

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CHAPTER 1

Introduction

Contents

1.1 Background

The term diabetes mellitus (hereafter referred to as diabetes) is a combination of the Greek word "diabetes" meaning "to pass through", and the Latin word "mellitus" meaning "sweet like honey" [1, 22, 53, 112]. This term is surprising appropriate if one considers the long history of diabetes. The earliest mention of a disease resembling that of diabetes may be found in Egyptian papyrus dating as far back as 1500 BC, where patients are described to have suffered from excessive thirst and frequent urination [53] — symptoms which are, nowadays, often associated with the diabetes disease. It was only, however, during the third century BC when Apollonius of Memphis coined the term "diabetes", which is regarded as the earliest reference to the disease [53, 112]. Due to a poor knowledge of anatomy, pathophysiology and lack of diagnostic tools, the diabetes disease perplexed physicians for many years [53, 112]. Physicians in antiquity, however, still observed the distinctive features and characteristics of the disease and even proposed several remedial approaches.

At the end of the fifth century, Sushruta, a famous Indian surgeon, referred to the diabetes disease as *Madhumeha* (meaning "honey-like urine"), and identified the sweet taste of the urine as belonging to those with the diabetes disease [53]. Sushruta discovered that ants may be used to test for diabetes. If the ants were attracted to the urine, this was a sign that it contained high sugar levels. Sushruta also found that the diabetes disease typically affected rich, upper class people who often consumed excessive amounts of rice, cereals and sugar [22, 53, 112]. In the seventh century, Chen Chuan, a Chinese physician, also made reference to the disease, which he termed *Hsiao kho*, characterised by symptoms of intense thirst, frequent urination (which was sweet to the taste) and blurred vision [1, 22, 53]. Both Sushruta and Chen also discovered that there were different types of diabetes. It was observed that a variation of the disease (which is now known as type 2 diabetes) was generally more common in people who were heavier in weight [1, 53]. In order to treat the disease, Chen's colleague, Li Hsuan, proposed the abstinence from salt, wine and sex [53].

At the turn of the eighth century, physicians began to observe the inclination of diabetics to develop skin infections, such as ulcers, as well as eyesight difficulties [53, 112]. A more thorough documentation of the diabetes disease is attributed to Avicenna, an eleventh-century Arabo-islamic physician, who wrote a textbook titled "El-Kanun" (Canon of Medicine) [53]. In his book, Avicenna mentioned that gangrene and sexual dysfunction are possible complications associated with the diabetes disease. Moises Maimonides, a medieval scholar, also contributed to describing the diabetes disease in detail, including the symptom of acidosis [53]. In 1776, Matthew Dobson, an English physician, also verified that the urine of diabetics has a sweet-tasting feature [1, 22, 53]. In one of his articles published in the *Journal of Medical Observations and Enquiries*, Dobson measured the glucose in urine and found the levels to be significantly higher in those with diabetes [70]. Furthermore, Dobson also identified that diabetes may be chronic in some people, but fatal in other cases, which clarified a significant differences between type 1 and type 2 diabetes [53].

Ancient Egyptians, Indians, Chinese, Arabs, medieval scholars and mid-modern physicians all contributed to the understanding of the clinical signs and symptoms associated with the diabetes disease [1, 22, 53, 112]. These noteworthy protagonists in the history of diabetes contributed significantly to the current understanding of the disease, as well as to its diagnosis and treatment, thus paving the way for further research in the new medical sub-speciality of diabetology [53].

In the present day, the readily-accessible supply of processed food has weakened the association between wealth and diabetes [53]. Obesity, diet and a lack of exercise are, however, still significant risk factors associated with developing type 2 diabetes. Type 2 diabetes has often been described as a "disease of civilisation" [156]. Technologies, such as those involved in food production, farming and food processing, allow populations to ingest more calorie-dense food than in the past in far greater amounts [53, 156]. The advancements in transportation releases people form the need to walk, while the shifting from manual labour to machines reduces the amount of energy expended in daily business. The *World Health Organization* (WHO) describes the advancement of technology as the *surfeit of calories and dearth of energy expenditure* [156] and a significant contributor to the increase in chronic diseases like diabetes.

Since 1988, the WHO has collected data related to the prevalence of diabetes in adult communities throughout the world [56]. The analysis of this data has revealed three key findings [56]. First, it is evident that a diabetes epidemic has occurred (or is currently occurring) in adults worldwide. Secondly, this diabetic trend seems to be strongly related to socio-economic and lifestyle changes. Lastly, the populations in developing countries are now regarded as being the *most* at risk of bearing the negative effects associated with the diabetes disease.

Diabetes was once regarded as a disease affiliate more with the developed world — now it is becoming increasingly widespread in developing countries which presents many new challenges [35, 43]. The diabetes mellitus disease perplexed physicians in antiquity and continues to do so in the modern era. It is now, however, not the workings of the disease itself that baffles health care professionals, but rather the solution to better manage the significant diabetic prevalence increase in both developed and developing countries worldwide.

1.2 Problem statement

The increasing prevalence of diabetes in the world is a widespread concern [44]. Globally, there are an estimated 366 million people living with diabetes, where the *International Diabetes Federation* (IDF) predicts that this number will increase to over 500 million worldwide by 2030 [47, 85]. Current epidemiological data shows that 9% of adults worldwide have the diabetes disease [47], while it is estimated that 1.5 million people died from diabetes in 2012. According to the WHO [133], diabetes is projected to be the seventh leading cause of death by 2030. A person with type 2 diabetes is also three times more likely to develop *cardiovascular disease* (CVD), of which 70% will likely die as a result of this disease [103]. In addition, premature mortality as a result of diabetes results in an estimated ten years of life lost per diabetic [103].

While improvements have been made in the epidemiology and management of diabetes in the developed world, the same advances have not been made in South Africa [44]. South Africa is also experiencing an increasing prevalence of diabetes alongside other *non-communicable diseases* (NCDs) [85]. In South Africa, this diabetic trend is emerging in a region confronted with high rates of communicable diseases, such as the highest global prevalence of HIV, as well as Tuberculosis [35, 85]. Additionally, diabetes is a component cause of several other fatal diseases [35, 85]. These diseases include both NCDs, such as CVD and renal disease, and communicable diseases, such as HIV and Tuberculosis, which have a considerable impact on morbidity and mortality in South Africa [35]. In addition, the prevention and treatment of diabetes in South Africa is a complex process, involving numerous role-players and stakeholders, such as government agencies, the health care system, communities and diabetic patients. It is, therefore, necessary to consider diabetic health care in South Africa from a complex systems perspective with significant non-linear interactions.

Despite national diabetic policy implementation outlined in the *Management of type 2 diabetes in adults at primary care level* policy published in 2014 [103], the prevalence of type 2 diabetes has, steadily increased in South Africa from 4.5% in 2010 to 7% in 2017 [47]. In addition, the proportion of all diabetic-related deaths in South Africa has increased from 5.1% in 2014 to 5.5% in 2017. This increase in the prevalence of type 2 diabetes, along with the increased diabetes-related mortality, raises questions regarding the effectiveness of existing diabetes interventions in South African diabetic policy.

1.3 Research aim

The aim of this research is to investigate and evaluate existing diabetic intervention strategies so as to provide insight on how the diabetes disease can be more effectively managed within South Africa. In this research, the effects of a variety of diabetic policy intervention scenarios should be evaluated so as to determine the most effective policies for addressing the management of diabetes within South Africa. Using the results of the intervention scenarios, policy considerations should be made to better inform policy strategy and intervention recommendations to reduce diabetes-related mortality in South Africa.

The aim of this research should be realised through the development of an appropriate model of the South African diabetic health care system. This model should be capable of analysing and managing complex feedback systems from a holistic perspective which may serve as a useful analysis tool for understanding and studying diabetic populations in South Africa, whilst also being capable of evaluating the effectiveness of policy interventions to better manage the diabetes disease.

1.4 Research objectives

The following eight objectives are pursued in this project:

I To *determine* if a need exists to investigate existing intervention strategies for the management of diabetes in South Africa.

II To *develop* a set of requirement specifications so as to determine an appropriate method for investigating intervention strategies for the management of diabetes in South Africa.

III To *evaluate* and *identify* a modelling approach that most appropriately meets the requirement specifications developed for Objective II.

IV To *design* and *implement* a model that correctly models the dynamics of diabetic health care, as well as the diabetes populations, in South Africa.

V To *validate* and *verify* the performance and execution of the model in respect of each new addition, both by model output or, where necessary, expert opinion.

VI To *develop* scenarios and *test* intervention strategies in the system dynamics model so as to determine the strategies most effective in managing diabetic health care in South Africa through policy formulation.

VII To *recommend* policy strategy and intervention recommendations for the management of diabetes in South Africa.

VIII To *recommend* sensible follow-up work which may be pursued in the future for the purpose of extending the work completed in this thesis.

1.5 Research scope

When considering the title of this research, *Investigating intervention strategies for the management of diabetes in South Africa: A system dynamics approach*, it is apparent that this research endeavour appears quite ambitious. Indeed, a research project of this magnitude would naturally consist of two components:

I The development of a system dynamics model which can correctly depicts the causal relationships found within the diabetic health care system in South Africa.

II The acquisition of accurate data pertaining to the various aspects of the health care system in South Africa, the availability of resources, and various diabetes-related interventions and measures, in addition to the generation of regression models for non-linear behaviour between these variables.

Data relating to the South African health care system, the availability of resources, and various diabetes-related interventions and measures are, however, largely unavailable in South Africa — these data are either not open to the public, have not been collected or do not exist. Instead, the aim of this research is focused on accomplishing the aforementioned Component I, where a system dynamics model is developed so as to correctly identify and depict the various causal relationships between stakeholders, resources and patients found within the diabetic health care system in South Africa. In lieu of the data described in Component II, reasonable assumptions, based on mental models and literature, are made and justified throughout this research.

Furthermore, due to the complexities associated with the diabetic health care system in South Africa, the scope of this research is limited by the following overall research and model assumptions.

I The model assumes and simulates the South African public health care system as a fully-contained system and is not influenced by the South African private health care system. South Africa is also modelled as an isolated country.

II Although many variations of diabetes exist, the model only considers and investigates type 2 diabetes. This is primarily due to type 2 diabetes afflicting 95% of those diagnosed with diabetes [85], therefore, demonstrating the importance to investigate this specific variation of the disease.

III In order to understand the effects of the alternative interventions on the diabetic populations, the research scope is limited to modelling the dynamics of the diabetic populations. Consequently, any policy strategy and intervention recommendations are, therefore, made based on the effects of the diabetic populations and not with regard to resource allocation or cost of intervention associated with an intervention.

IV It is important to note that, while a variety of diabetic complications arise, certain complications only affect a person's quality of life and are non-fatal in nature. Diabetic complications, such as heart disease and kidney disease, do, however, lead to death. Since this research focuses on the dynamics of the diabetic populations, as mentioned in Assumption III, only fatal diabetic complications are considered when modelling the dynamics of diabetics with complications.

V The model assumes that South African legislative and other qualifying criteria as stipulated in the *Management of type 2 diabetes in adults at primary care level* policy are met.

VI The model assumes that all health care professionals are well-trained and acclimatised to their work task, and are able to perform the diabetic treatment procedure outlined in the *Management of type 2 diabetes in adults at primary care level* policy.

VII The model is limited to the South African adult population due to the relatively low prevalence of diabetes in people below eighteen years of age and the lack of data available regarding the number of diabetics in the South African adolescent population. [103].

1.6 Research methodology

The methodological procedure followed in this research to investigate existing intervention strategies for the management of diabetes in South Africa, is as follows:

1. *Conduct* a survey of the literature pertaining to:
    a. the diabetes disease;
    b. the South African health care system;
    c. the prevalence of diabetes in South Africa;
    d. policy within the public health care context;

e. policy analysis methods;
f. international diabetic policy;
g. South African diabetic policy and intervention strategies; and
h. modelling approaches and techniques, in order to develop context in the investigation of existing intervention strategies for the management of diabetes in South Africa.

2. *Conduct* thorough policy analyses to characterise diabetes health care properties, as well as to *identify* current policy intervention strategies in South Africa so as to determine if there exists a need to investigate existing intervention strategies for the management of diabetes in South Africa.

3. *Develop* a set of requirement specifications, based on policy analyses of Step 2, so as to determine an appropriate method to investigate intervention strategies for the management of diabetes in South Africa.

4. *Evaluate* and *identify* a modelling approach that most appropriately meets the requirement specifications developed in Step 3, and *develop* a proficiency in the selected modelling approach.

5. Iteratively *construct* the model to investigate the dynamics of diabetic health care and diabetic populations of South Africa.

6. *Validate* and *verify* the performance and execution of the model in respect of each new addition, both by model output or, where necessary, expert opinion.

7. *Develop* scenarios based on existing intervention strategies for model testing.

8. *Test* intervention strategies so as to determine the most effective strategies for managing diabetic health care in South Africa through policy formulation.

9. *Recommend* policy strategy and intervention recommendation guidelines for the management of diabetes in South Africa.

1.7 Research organisation

Excluding this introductory chapter, this research contains a further six chapters partitioned into three parts. Chapter 2 is the first of three chapters which consists of a review of literature pertaining to the study — all contained within Part I of this research. Chapter 2 specifically focuses on the diabetes mellitus disease in South Africa. In this chapter, the diabetes mellitus disease is first defined. Thereafter, the disease is classified according to its clinical stages and aetiological features, followed by a discussion on the diagnosis and screening of diabetes, as well as the organisation of diabetic care and arising diabetic complications. An analysis of the South African health care system is then presented. Finally, a conceptual framework is identified and applied to the diabetic health care system in South Africa.

Chapter 3 is the second of three literature review chapters and specifically focuses on diabetic policy and intervention strategies. The concept of policy is first defined, followed by the introduction of various policy analysis methods. Global diabetic policy is then presented, as well as intervention strategies that which have successfully managed other NCDs. A systematic review of international diabetic policies is then conducted so as to determine the standard of South

African diabetic policy in comparison to international diabetic policy, as well as to identify alternative diabetic intervention strategies implemented by other countries. Finally, this chapter concludes by analysing South African diabetic policy using appropriate policy analysis methods.

Chapter 4 is the third of three literature review chapters and specifically focuses on reviewing the available modelling approaches which may be applied in the context of this research. This chapter begins by developing a set of requirement specifications so as to identify an appropriate approach for the modelling of the diabetic health care system in South Africa. Thereafter, modelling approaches of a general nature are discussed and presented, followed by a detailed description of the most notable modelling approaches. The set of requirement specifications are then used to evaluate the aforementioned modelling approaches in order to determine the most appropriate approach to model the dynamics of diabetic health care in South Africa with the purpose of investigating existing intervention strategies for managing the diabetes disease. Finally, the modelling approach adopted for this research is further described.

Part II of this research comprises Chapters 5 and 6 which collectively draw upon the literature uncovered in Part I to propose a model that is able to investigate the effects of intervention strategies for managing the diabetes disease in South Africa. At the onset of Chapter 5, the problem identified for research is formally articulated. The problem is then conceptualised through the formulation of a dynamic hypothesis, followed the presentation and discussion of the model developed in an appropriate modelling software. The validation and verification of developed model is then conducted by means of model output analysis and expert opinion.

Chapter 6 presents and discusses the results obtained from the model. First, scenarios are developed based on existing intervention strategies for testing in the aforementioned model. The model results of the alternative intervention strategies are then presented and discussed. Using these scenario results, policy considerations are then presented so as to provide insight into the complex and dynamic diabetic health care system, as well as to highlight effective causal relationships which exist within this system.

This thesis closes in Part III with Chapter 7. A summary of the work presented in Chapters 1–6 is first presented, followed by the research contributions and limitations of this work. Finally, recommendations in the form of possible future follow-up work are presented.

1.8 Chapter 1 conclusion

In this chapter, the background of this research study was introduced. A brief introduction of the diabetes disease was presented, as well as the problem statement regarding the growing diabetic prevalence in South Africa. The research objectives formally addressed the research aim of this study, while the research methodology discussed the steps needed to achieve the research objectives. A research scope was then presented which stipulated sensible boundaries for this research. Lastly, the chapter concluded with a description of the organisation of this thesis.

Part I

Review of literature

CHAPTER 2

Contextualisation of Diabetes Mellitus in South Africa[1]

Contents

In order to highlight the need to investigate existing diabetic intervention and management strategies, in fulfilment of Research Objective I, this chapter explores: (i) The diabetes disease, (ii) the South African health care system, and (iii) the state of diabetes in South Africa. At the onset of the chapter, diabetes mellitus is first defined and then classified according to its clinical

[1]A significant portion of the text in §2.2 and §2.3 has been reproduced from a conference article which was published as part of this research. The article citation is: Thomas V, de Kock I & Bam L. (2018). "Considering the need for alternative intervention strategies for the management of diabetic policy formulation in South Africa." Proceedings of the *SAIIE29 Conference, 24th–26th of October 2018, Spier, Stellenbosch, South Africa*, pp. 295–306.

stages and aetiological features. The diagnosis and screening of diabetes is then discussed, and the organisation of diabetic care is presented along with associated diabetic complications. In §2.2, a brief overview of aspects related to the South African health care system is then presented as a mechanism of contextualising this research. This overview focuses on the efficiency of the system, inequality between the public and private health care system, and the increased burden of disease in South Africa. Specific aspects of diabetes in South Africa are then presented in §2.3 which includes its growing prevalence within the country. This is followed by a discussion of the financial implications and management of diabetes within South Africa, highlighting the need to address diabetes by employing diabetic management intervention strategies. Focus subsequently shifts in §2.4 to determining the level of analysis needed for this research by analysing the components of the diabetic health care system.

2.1 Diabetes mellitus

The increasing prevalence of diabetes in the world is a widespread concern [44]. According to predictions by the International Diabetes Federation, the prevalence of diabetes is expected to increase globally from 415 million in 2015 to 642 million by 2040 [47, 85]. Additionally, diabetes is often associated with contracting several other, often life threatening, diseases [35]. These include both non-communicable diseases, such as CVD and renal disease, and communicable diseases, such as pneumonia and tuberculosis, which have a considerable impact on morbidity and mortality [35]. In addition, the prevention and treatment of diabetes is a complex[2] process [71], involving numerous role-players and stakeholders, such as government agencies, the health care system, communities and diabetic patients.

This section begins by defining diabetes mellitus, together with its typical symptoms and health effects. The disease is classified according to its clinical stages and aetiological features. The diagnosis and screening of diabetes is then discussed. Finally, the organisation of diabetic care is presented.

2.1.1 Definition of diabetes mellitus

Diabetes mellitus is classified as a metabolic disorder with heterogeneous aetiologies, and is characterised by chronic hyperglycaemia and disturbances of carbohydrate, protein, and fat metabolism caused by defects in insulin secretion, insulin action, or both [102, 103, 126, 132]. The long-term health effects of diabetes include the development of nephropathy, retinopathy, and neuropathy [126, 132]. Diabetics are also at an increased risk of developing cardiac, peripheral arterial, and cerebrovascular disease [126]. Diabetics also possess characteristic symptoms which may include thirst, polyuria, blurred vision, weight loss, excessive urine production, significant amounts of sugar in the blood and urine, acidosis, sexual dysfunction, and increased hunger [102, 103, 126, 132]. The most severe clinical manifestation of diabetes is the ketoacidosis (or non-ketotic hyperosmolar) state, which may lead to stupor, coma, and, in the absence of treatment, death [102].

There are several pathogenic processes which are involved in the development of diabetes. These include processes that impair or destroy the function of the pancreatic beta cells with consequent insulin deficiency and others that result in resistance to insulin action [102, 132]. Abnormalities

[2]The term 'complex' in this research is defined as system (in this case, the diabetic health care system) which consists of many different entities that are linked in a close or complicated way [65].

in carbohydrate, protein and fat metabolism are due to the deficient action of insulin on target tissues, resulting from insensitivity to or lack of insulin (or both) [102, 132].

Diabetic symptoms are, however, often not severe or may be entirely absent. Consequently, in the absence of routine diabetic screening, hyperglycaemia is sufficient enough to cause pathological and functional changes, and may be present for a significant period of time before diagnosis [102, 103]. There is, therefore, a considerable need for improved screening of diabetes, particularly due to the fact that a significant percentage of cases remain undiagnosed [103].

2.1.2 Classification of diabetes and other categories of glucose tolerance

The classification of diabetes and other categories of glucose tolerance encompasses both the clinical stages and aetiological types of these conditions [102, 132]. This sub-section begins by describing the clinical stages of diabetes followed by the aetiological classification of the disease.

Clinical stages of diabetes

When the clinical stages of diabetes are considered, the spectrum of glucose tolerance extends from normoglycaemia, to intermediate hyperglycaemia, which may consist of *Impaired Fasting Glucose* (IFG) or impaired glucose tolerance (IGT) [102, 103, 132].

A fasting venous plasma glucose concentration of less than 6.1 mmol 1^{-1} or 100 mg.dl^{-1} has been defined as a 'normal' non-diabetic value (or normoglycaemia state) [102, 103, 132]. Although apparently arbitrary, these values have been observed in people with proven normal glucose tolerances [132].

Stage 1 of diabetes is that of *pre-diabetes*, in which both IFG and IGT may occur [102, 103, 132]. This stage includes patients with a *Fasting Plasma Glucose* (FPG) level of between $100 - 125$ mg.dl^{-1} and an IFG level of between $6.1 - 6.9$ mmol 1^{-1} [102, 103]. Approximately, 5–10% of people with pre-diabetes will progress to diabetes per year, with the same proportion reverting back to normoglycaemia [111]. Observational evidence has shown associations between pre-diabetes and early forms of nephropathy, chronic kidney disease, small fiber neuropathy, diabetic retinopathy, and an increased risk of macrovascular disease [102, 111].

Stage 2 of the clinical stages of diabetes comprises of diabetics living without complications [102, 103, 132]. This group includes patients with a FPG and IFG levels higher than 126 mg.dl^{-1} and 7.0 mmol 1^{-1}, respectively [102, 103]. These patients may or may not have insulin resistance or display classic hyperglycemia symptoms, which include increased urinary frequency, thirst, hunger, and unexplained weight loss [102, 103].

When mild diabetic complications develop, Stage 3 of the clinical stages is encountered [102, 103, 132]. These mild complications typically include microalbuminurea and mild diabetic retinopathy [102, 132]. Patients may or may not have hyperglycemia, or higher than normal levels of FPG [102].

Stage 4 of the clinical stages of diabetes comprises diabetics with absolute insulin deficiency [102, 103, 132]. This stage includes patients with hyperglycemia and absolute insulin deficiency based on clinical and/or laboratory evidence. Patients may also have mild to moderate complications, which may include diabetic nephropathy without kidney failure or diabetic retinopathy without proliferative diabetic retinopathy [102]. Laboratory evidence includes levels of fasting plasm insulin lower than the normal lower limit on a laboratory's measurement method [102, 103].

Stage 5 of the clinical stages of diabetes comprises diabetics living with serious complications [102, 103, 132], which includes patients with hyperglycemic crises, as well as microvascular and macrovascular complications. Patients may have hyperglycemia, as well as higher or lower than normal levels of FPG [102]. Diabetic ketoacidosis and the hyperosmolar hyperglycemic state are the two most serious acute metabolic complications which may occur in this stage [102]. The diagnostic criteria for diabetic ketoacidosis includes FPG levels larger than 250 mg.dl^{-1}, whereas the diagnostic criteria for hyperosmolar hyperglycemic includes FPG levels larger than 600 mg.dl^{-1} [102, 103, 132]. Microvascular complications include retinopathy, nephropathy, neuropathy, and cardiomyopathy, while macrovascular complications include coronary heart disease, cerebrovascular disease, proliferative diabetic retinopathy, peripheral arterial disease, amputation, and foot ulceration [102].

Aetiological classification of diabetes mellitus

The aetiological types of diabetes are typically classified as being either of type 1, type 2 or gestational diabetes [126]. Type 1 diabetes, which accounts for only 5-10% of diabetic cases, is referred to as “insulin-dependent” diabetes and typically emerges during childhood [85, 126]. This variation of diabetes is an autoimmune condition, where the human body attacks its own pancreas with antibodies. After significant damage, the pancreas of a person with type 1 diabetes is be unable to produce insulin [126]. A number of medical risks are associated with type 1 diabetes, such as diabetic retinopathy, diabetic neuropathy, and diabetic nephropathy [102, 126]. Furthermore, persons with type 1 diabetes have an increased risk of heart disease and stroke. Type 1 diabetes requires adequate treatment to maintain blood sugar levels within a target range. Treatment typically includes taking several insulin injections daily or using an insulin pump, monitoring blood sugar levels, and eating a healthy diet that portions carbohydrates throughout the day [126].

The most common form of diabetes is type 2 diabetes which for 95% of diabetic cases in adults [85]. Type 2 diabetes was previously almost-only observed in middle age or older adults, and was, therefore, referred to as ‘adult-onset’ diabetes [126]. With the rise of obesity in children, however, type 2 diabetes is now being increasingly diagnosed in young children and teenagers [85]. Furthermore, people who are classified as being obese are typically at a significantly higher risk of developing type 2 diabetes, together with the related medical problems. In the case of type 2 diabetes, the pancreas is typically capable of producing some insulin. The insulin is, however, either insufficient for the needs of the body, or the cells of the body are resistant to the insulin [126]. Type 2 diabetes is often milder than type 1, but may still, however, cause major health complications, particularly in the body’s blood vessels that nourish the kidneys, nerves, and eyes. Type 2 diabetes also increases the risk of heart disease and stroke [102, 126]. There currently exists no cure for diabetes. Type 2 diabetes may, however, be controlled through proper weight management, nutrition, and exercise. Diabetes medications may also be acquired if the disease continues to worsen.

Other specific types of diabetes are linked to a wide variety of conditions which are primarily genetically modified forms of the diabetes disease or associated with other diseases or medications [102]. The clinical distinction between type 1, type 2, and other specific types of diabetes may often be challenging to identify, particularly in adolescents and young adults. Type 1 and, more specifically, type 2 diabetes are essentially clinical diagnoses of exclusion (*i.e.* they both require the practitioner to at least consider and reasonably exclude other causes of diabetes mellitus) [102]. It is estimated that approximately 15% of diabetic patients in general practice are misdiagnosed or misclassified, which leads to important therapeutic and prognostic implications.

Table 2.1 illustrates the clinical differences between type 1 and type 2 diabetes in adolescents and young adults [103].

TABLE 2.1: *Clinical differences between type 1 and type 2 diabetes [103].*

Type 1 diabetes	**Type 2 diabetes**
Typically younger (<30 years)	Usually older, but increasing in adolescents and young adults increasing
Usually lean weight	Mostly overweight or obese
Onset is acute	Onset is gradual
Almost always symptomatic (polyuria, polydipsia, weight loss)	Often asymptomatic
Prone to ketosis and often ketoacidotic at diagnosis	Not usually ketosis prone, but ketoacidosis may be present at diagnosis
Diagnosis - usually has enquivocal hyperglycemia	Diagnosis often during screening
Insulin necessary from diagnosis for survival	Usually controlled with non-insulin therapies, or may need insulin for symptom control
Otherwise normally healthy	Often have comorbidities, such as hypertension, dyslipidaemia, sleep apnoea, myocardial infarction or stroke

Maturity onset diabetes of the young (MODY) denotes a group of autosomal dominant single gene disorders resulting in impaired insulin secretion with the onset of diabetes in adolescence or early adulthood [29, 37, 102]. These patients typically have mild or no symptoms, have a family history of early diabetic onset (typically before the age of 25), and typically lack the phenotype of the obese insulin-resistant type 2 diabetic patient [29, 37]. MODY is estimated to account for approximately 1–2% of diabetic cases, and is often misdiagnosed as type 1 or type 2 diabetes [102]. The differences in treatment and prognosis, together with the need for genetic counselling, requires a clinician to have a strong index of suspicion for MODY in patients with type 2 diabetes before the age of 25 [29, 37, 102].

Latent autoimmune diabetes of adulthood (LADA) is a form of type 1 diabetes often misdiagnosed as type 2 diabetes [87, 102]. LADA diabetes is characterised by a slower autoimmune destruction of beta cells than is commonly observed in type 1 diabetes, and hence a slower onset of hyperglycaemia is also present, which is more typically observed in cases of type 2 diabetes [87, 102]. Phenotypically, patients with LADA are usually older than the typical type 1 diabetic patient (*i.e.* older than 25 years) and are more likely to be non-obese and lack the strong family history of diabetes which is typically associated with type 2 diabetes [87, 102]. These features are, however, not invariable. Approximately 10% of patients over the age of 35, previously labelled as having type 2 diabetes, may actually have LADA [102].

The final variation of diabetes is triggered by pregnancy and is referred to as *gestational diabetes* [102, 126]. This form of diabetes is often diagnosed in middle or late pregnancy. Since high blood sugar levels in a mother are circulated through the placenta to the baby, gestational diabetes must be controlled to protect the growth and development of the baby [102, 126]. It has been reported that the rate of gestational diabetes occurs in between 2%–10% of pregnancies [126]. On the contrary, gestational diabetes typically resolves itself after pregnancy. The occurrence of gestational diabetes does, however, increase the risk of the mother developing type 2 diabetes later in life by about 10% [126].

2.1.3 Diagnosis of diabetes and other categories of intermediate glycaemia

Diabetes can be diagnosed at any point during a spectrum of clinical presentations [102, 103]. These occurrences include low-risk individuals who incidentally happen to have glucose testing in a random screening scenario, to individuals identified as having a high-risk of diabetes during routine consultations for unrelated health matters in an opportunistic screening scenario, to those who are deliberately identified and tested because of their high-risk status in a targeted screening scenario.

Diabetes may be diagnosed based on the results of a number of tests. These diabetic tests include the plasma glucose criteria value, the FPG value, the *Two-hour Plasma Glucose* (2-h PG) value after a 75g *Oral Glucose Tolerance Test* (OGTT), a random plasma glucose in symptomatic individuals, or the glycated haemoglobin HbA_{1c} criteria [102, 103]. No one test is preferred over another for diagnosis. For clinical purposes, the diagnosis of diabetes should always be confirmed by repeating the test on another day using the same test [103]. The criteria for the diagnosis of diabetes and categories of intermediate hyperglycaemia according to the various diagnosis tests is shown in Table 2.2 [103].

Table 2.2: *Criteria for the diagnosis of diabetes and categories of intermediate hyperglycaemia [103].*

Diagnostic test	IFG	IGT	Diabetes
RPG	—	—	$\geq$ 11.1 mmol/L if classic symptoms of diabetes or hyperglycaemic crisis is present; or
FPG	6.1–6.9 mmol/L	$<$ 7.0 mmol/L (if measured)	$\geq$7.0 mmol/L; or
2-h PG OGTT	$<$ 7.8 mmol/L (if measured)	7.8–11.0 mmol/L	$\geq$ 11.1 mmol/L; or
Glycated haemoglobin HbA_{1c}	—	—	$>$ 6.5%

In patients with classic symptoms of diabetes (*i.e.* polyuria, polydipsia, weight loss or explicit hyperglycaemia), only a single test is sufficient in order to confirm the diagnosis of diabetes [102, 103]. Severe hyperglycaemia detected under conditions of acute infective, trauma, cardiovascular, or other stress may, however, be transitory and should not be regarded as a diagnosis of diabetes until subsequently confirmed [103].

2.1.4 Screening for type 2 diabetes in adults

Screening should only be carried out within a health care setting [102, 103]. Community screening outside a health care setting is not recommended, as individuals with abnormal positive tests may not seek or have access to appropriate follow-up testing and care. Additionally, there may be failure to ensure proper repeat testing for those who test negative for diabetes [103]. Furthermore, these screenings may also be poorly targeted and fail to reach groups most at risk by inappropriately testing those at a low risk or those already diagnosed with diabetes [102, 103]. Similarly, random screening for all adults is not recommended until after the age of 45 [102, 103]. The criteria and indications for the opportunistic screening of type 2 diabetes in asymptomatic adults is described in Table 2.3 [103].

TABLE 2.3: *Criteria for screening for type 2 diabetes in asymptomatic adults [103].*

Indications	High-risk individuals: All adults (any age) with BMI > 25 kg/m^2 (overweight or obese), as well as one or more additional risk factors for future diabetes • physical inactivity • hypertension (Blood pressure > 140/90 mmHg) • family history of diabetes (First degree) • dyslipidaemia (serum high-density lipoprotein [HDL] cholesterol < 0.90 mmol/L or triglycerides > 2.82 mmol/L) • polycystic ovarian syndrome • high-risk ethnic group (those of South Asian descent) • cardiovascular disease history • history gestational diabetes mellitus or baby > 4 kg at birth • IFG or IGT (previously diagnosed) • other conditions associated with insulin resistance If no risk factors: Age ≥ 45 years
Frequency	At 3 year intervals if tests are normal More frequently, based on initial result and risk status (annually in those with IFG, IGT, or those with multiple risk factors)
Test method	FPG, 2 hour PG (OGTT) or HbA1c OGTT is the preferred test in high-risk individuals

2.1.5 Diabetes treatment procedure

Since diabetes is a complex disorder, a systematic approach for the organisation of diabetic care and its treatment procedure is crucial [103]. The elements in this approach for well-organised diabetic care includes well-trained and dedicated health care professionals, functioning equipment, a regular and sustainable supply of medication and consumables, management and health care referral protocols, and legible patient records [103]. Furthermore, regular audits need to be instituted in order to review the implementation of interventions so as to improve the standards of care and service delivery.

In order to better manage diabetic care at a clinic level, appropriately trained health care professionals dedicated to the management of chronic diseases are necessary [102, 103]. Adequate space is required for individual consultation, as well as for group education. Additionally, protocols and guidelines covering screening, regular care and referrals are also needed. Basic equipment as per specified standards and norms, as well as pharmaceuticals to treat diabetes, is required in a *Primary Health Care* (PHC) facility [102, 103]. It is typically advised that diabetic patients visit their doctor three to four times a year depending on their treatment plan [102]. During the initial and follow-up consultations, specific aspects of the patient history and biochemistry are examined, and a physical examination is conducted to determine the treatment plan, as shown in Tables 2.4, 2.5 and 2.6 [103]. Follow up consultations are typically not as in-depth as the first visit, though patients are recommended to complete a physical exam at least once a year [102, 103]. The frequency of examinations and tests are based on the assumption that the last set of observations was normal. In the presence of abnormalities, the frequency of visits should be increased [102, 103].

Another important component of diabetic health care (which runs concurrently with the disease treatment procedure) is diabetes self-management education [102, 103]. Diabetic self-management education is a continuous process of facilitating knowledge, developing skills and ability, and encouraging motivation for self-management of diabetes which involves the active participation of the diabetic patient. It is largely agreed upon by the Academy of Nutrition, and Dietetics of America that diabetic self-management education should be presented by a trained health care professional during the initial and follow-up diabetic consultations [102]. The impact of this form of education was observed in a South African community-based programme where a 5% weight loss and 1% decrease in HbA_{1c} levels were achieved after four self-management education sessions [102]. It is, therefore, apparent that adequate and ongoing diabetic self-management education forms an integral component of diabetic care.

TABLE 2.4: *Patient history, physical examination, bio-chemistry and other activities recommended during the initial visit to a diabetes clinic [103].*

Initial visit		
History	*Physical examination*	*Biochemistry*
• Symptoms of hyperglycaemia and duration • Relevant family history • Other risk factors: – high birth-weight baby – gestational diabetes • Relevant medical history: – Co-morbid conditions – Symptoms of complications: ∗ Cardiovascular; neurological ∗ bladder and sexual functions (*i.e.* erectile dysfunction) ∗ Feet/vision ∗ Infections • Medication history – Current medicine use – Allergies to medication • Symptoms of hypoglycaemia • Vaccinations – Pneumococcal (date) – Influenza (date) • Lifestyle – Weight history – Physical activity – Eating pattern – Tobacco smoking – Alcohol consumption • Psycho-social – Depression – Cccupation – Family/community support • Home monitoring chart (if relevant)	• Weight, height and BMI • Waist circumference • Blood pressure • Feet – Inspection: oft tissue injuries, ulcers, infections, – Deformities, footwear – Monofilament assessment – Vibration sense using tuning fork, or pinprick sensation – Ankle jerk – Peripheral neuropathy – Foot pulses • Oral cavity – Dental caries – Gum disease • Eyes – Visual acuity – Direct fundoscopy (dilated pupils) indirect fundoscopy, or fundus photographs • Cardiovascular system • Injection sites (if appropriate) • Blood pressure	• Blood – Glucose – HbA_{1c} – Lipids – Creatinine – Potassium – HIV • Urine – Protein: Albumin/Creatinine ratio *Other activities* • Education – Lifestyle and behavioural changes including smoking cessation – Self-management – Nutrition advice, eating habits and meal planning • Goal setting • Pre-conception counselling/family planning (as appropriate) • Medication revision/adjustment • Immunisations

TABLE 2.5: *Patient history, physical examination, bio-chemistry and other activities recommended during the 3–6 month visit to a diabetes clinic [103].*

3–6 monthly visits until treatment goals are achieved		
History	*Physical examination*	*Biochemistry*
• Symptoms of hyperglycaemia and duration • Medication – Assess adherence and side-effects • Symptoms of hypoglycaemia • Lifestyle (as at initial visit) • Depression • Review home monitoring chart	• Weight, height and BMI • Waist circumference • Blood pressure • Feet – Inspection: Soft tissue injuries, ulcers, infections, deformities, footwear • Injection sites (if applicable)	• Blood – Glucose – HbA_{1c} *Other activities* • As at initial visit especially medication review

TABLE 2.6: *Patient history, physical examination, bio–chemistry and other activities recommended during the annual visit to a diabetes clinic [103].*

Annual visit		
History	*Physical examination*	*Biochemistry*
• As at initial visit	• As at initial visit • Screening for retinopathy: – Two yearly if last two examinations were normal – More frequent examinations in the presence of abnormalities	• As at initial visit *Other activities* – As at initial visit especially medication review

2.1.6 Management of diabetic complications

Several complications arise in the later stages of the diabetes disease (as discussed in §2.1.2) which affects the management of the disease within South Africa. These complications include (i) hypertension, (ii) CVD, (iii) chronic kidney disease, (iv) retinopathy, and (v) neuropathy and foot problems.

Hypertension (or high blood pressure) is a severe complication that increases the risk of heart disease and stroke [103]. The diagnosis criterion of hypertension in patients with type 2 diabetes is a blood pressure higher than 140/80 mmHg on two separate days [103]. According the *Management of type 2 diabetes in adults at primary care level* policy, the blood pressure of a diabetic must be measured at every clinic visit. The blood pressure should be measured in both arms during the initial consultation, and thereafter in the arm with the higher blood pressure. Those with diabetes-related hypertension are prescribed ACE inhibitors, which is a pharmaceutical drug used primarily for the treatment of hypertension and congestive heart failure [103].

Cardiovascular disease (or heart disease) accounts for 70% of all diabetic mortality [103], and is largely caused by the high prevalence of the hypertension among diabetics. Heart disease is responsible for almost one in six deaths or 17.3% of deaths in South Africa [39]. The risk of heart disease in people with type 2 diabetes is increased three-fold when compared with people without diabetes [103]. In terms of non-pharmacological therapy for diabetes-related heart disease, diet is the cornerstone of theory, with a particular focus on caloric intake, fat intake, fibre intake, and alcohol consumption [103]. In the case of pharmacological therapy, achieving the recommended cholesterol level is the primary goal of therapy for diabetes-related heart disease [103]. Statin medication, a class of lipid-lowering medications which reduce illness and mortality in those who are at high risk of CVD, are first line agents for lowering cholesterol in diabetic patients. Satin therapy should be added to non-pharmacological or lifestyle therapy regardless of baseline lipid levels.

Chronic kidney disease (or diabetic nephropathy) is a frequent, but potentially preventable long-term complication of the diabetes disease [103]. Approximately 40% of patients with diabetes will develop kidney disease. All type 2 diabetics patients should be screened for kidney disease at each consultation, as per the *Management of type 2 diabetes in adults at primary care level* policy [103]. In order to prevent the onset and progression of chronic kidney disease, the blood pressure of a diabetic patient should be carefully controlled and other cardiovascular risk factors need to be appropriately managed.

Diabetic retinopathy is a complication of diabetes which affects the eye by causing damage to the blood vessels in the tissue at the back of the eye [103]. It is approximated that around 40% of diabetics have diabetic retinopathy, while 8% have sight-threatening retinopathy. Diabetic retinopathy is, however, largely preventable and treatable. In order to prevent its onset or progression, as well as to reduce the incidence of diabetic retinopathy, it is recommended that a patient stops smoking and that their blood glucose is optimally controlled [103]. The regular and thorough eye examination through dilated pupils and testing of visual acuity during diabetic consultations should identify patients at risk of developing retinopathy as a diabetic complication [103].

Diabetic neuropathy is a type of nerve damage occurring as a result of diabetes and typically damages the nerves in the legs and feet, which accounts for approximately 20% of all diabetes-related hospital admissions [103]. In the case of this complication, minor trauma to the foot leads to skin ulceration and infection, which may ultimately result in amputation [103]. After amputation, the prognosis for the contra-lateral limb is generally poor. Regular examinations of the feet are needed for diabetics and are typically conducted in diabetic consultations. These examinations include an assessment of the skin for ulcers, fissures, corns, calluses, blisters, fungal infections, and signs of trauma, the bone for any deformities or prominent bony surfaces, and the nerves to test for loss of sensation [103].

2.2 South African health care system

During the past two decades, the South African government has aimed to improve the condition of the public health care system by outlining a clear model with a particular focus on PHC [71]. PHC in the case of South Africa refers to the first line of health care that a patient receives, at either a clinic, community health centre or district hospital. This may include the treatment of a disease, referral to more specialised care if required, and preventive care through health education for individuals, families, and communities [28]. The unavailability of PHC for the majority of the South African population during the apartheid era, however, led to a significantly disproportionate number of serious health problems and challenges, which was manifested in higher infant mortality rates, as well as lower life expectancies [71]. While the post-apartheid government has since developed a primary-centred health care model aimed at all South Africans, the quality of this PHC remains inadequate [71].

In order to comprehend the current state of the South African health care system, it is necessary to first investigate the ability of the system to provide health care for the South African public. Furthermore, the inequality between private and public health care, and the increased burden of disease experienced in South Africa, need to be analysed in order to develop context for this research, and is now further discussed.

2.2.1 Efficiency of the health care system

In 2014, The Economist reported on a study that performed a 166-country health outcome report comparing the health care performance and spending patterns of various countries [33]. Figure 2.1 displays the results of this study, where the health outcome of a country is plotted against the ranking on health care spending for that country. The outcome measure was a combined function of (i) adult mortality in 2012, (ii) life expectancy at 60 years of age, (iii) disability-adjusted life years, and (iv) health-adjusted life expectancy. This study found that health outcomes were directly correlated with health care spending [33]. According to the study, a country with a high health care spending ranking should be expected to also have a high ranking for health care outcomes. It is, therefore, surprising that, while South Africa ranks high in terms of spending, it is ranked significantly low in terms of health care outcomes.

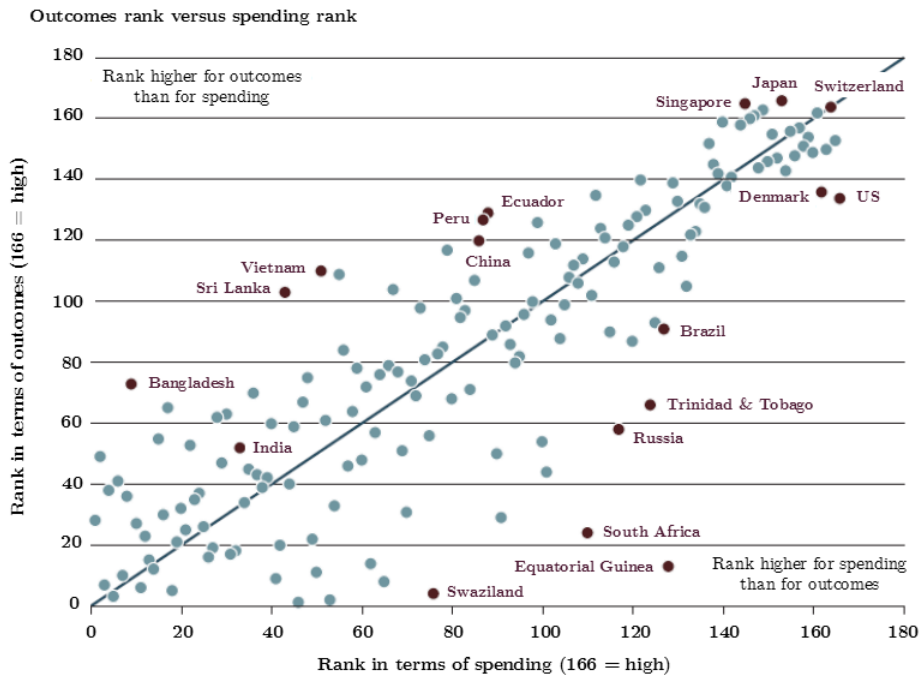


FIGURE 2.1: *Health care outcomes rank plotted against spending rank by country [33].*

This result is echoed by the Future Health Index study, commissioned by Dutch technology company Philips, which examined the current realities of how well the health care system of a country is prepared for the future in order to quantify the readiness of health systems to address global health challenges and build efficient and effective health systems [97]. The results of the study ranked South Africa last among 19 nations in a global survey which measured health care system efficiency against the ability to deliver maximum results at the lowest possible cost. The study included countries such as China, France, the United States, Argentina, United Arab Emirates and Brazil, and while the group achieved an average efficiency score of 10.5, South Africa only scored 4.4 [97].

Maillacheruvu [71] argues that the quality of PHC in South Africa is challenged by two major issues: The inequality between private and public health care, and the increased burden of disease experienced in South Africa. Maillacheruvu [71] further argues that, by addressing these issues, the health care outcomes of South Africa may be significantly improved. It is suggested that the inequality between public and private health care, as well as the increased burden of disease, is augmented by the historical struggles induced by the economic, political, and societal structure of the apartheid era [71]. These two issues are now further addressed.

2.2.2 Inequality between private and public health care

Health care in South Africa varies from the most basic PHC offered by the state, to highly specialised health services available in both the public and private sector [106]. In 2015, the total health expenditure per capita was USD 570, where the total health care expenditure formed 8.9% of the South African GDP [38]. According to the National Treasury's Fiscal Review [106], the South African GDP spent on health was split almost equally between the private health sector (48.5%) and the public sector (49.2%). The remaining 2.3% was donated and spent by NGOs. While the private and public sector both receive a similar share of the GDP for health care, the private health care sector only services an estimated 16% of the South African population, while the remaining 84% of the population relies on public health care services [38, 106].

In addition to the disparate patient populations between private and public health care, the number of health care providers within each system is also disproportionate. The WHO estimates that only 30% of all South African physicians work in the public sector, despite the public health care sector serving 80% of the population [54]. The relatively lower number of health care providers, along with the increased number of patients in the public health care system, results in an overburdened public care system, when compared to that of the private sector. It is also argued that public health care workers are overworked and thus, making it even more challenging to provide the same level of personalised services as the private sector [123].

In addition to the disproportionate number of health care workers in the public and private health care sectors, the economic divide between the rich and the poor also contributes to the persisting inequality between the two health care sectors. To further illustrate the extent of the inequality, it was reported in 2007 that South Africa had the worlds 10^{th} highest Gini index at 0.578, which is a measure of income inequity among a nations population [109]. The economic divide in South Africa has created a separation within the national health care system, and, as a result, has developed a considerable discrepancy between the resources used by public health care and the private sector.

Another consequence of the economic divide between public and private health care is the poor utilisation of the health care referral system [79]. Referrals between public clinics, community health care clinics and district hospitals are standard practice [32]. The referral system begins at PHC clinics as the first step in the provision of health care [33]. If the clinic cannot assist, the second step in the referral system is refer the patient to a community health center. The third step in the provision of health care is the district hospital. Thereafter, patients may be referred to secondary, tertiary, or quaternary level of care [33]. It was, however, noted by Mojaki [79] during a study conducted at the Dr JS Moroka District Hospital in the Free State that the majority of patients passing through the outpatient department had bypassed the referral system by means of self-referral. More than 50% of these patients could have been managed at PHC clinics or community health centers — this finding is echoed by a similar study conducted by Rutkove [96] at the King Edward VIII Hospital in Durban. Long waiting times (close to 6 hours) in the hospital would likely have been reduced if patients were managed at their nearest PHC facility.

Mojaki [79] found that the primary reason for patients bypassing PHC facilities was their perception of the superior care and resource availability at hospitals. This perception may be rooted in the inadequacy of PHC available to non-white South Africans during the apartheid era. Other cited reasons included dysfunctional community health centers and lack of education about the referral system among patients and health professionals. In addition, less than 2% of patients were educated on the referral system, and none had been charged the bypass fees despite the provincial policy. Mojaki [79] argues that the tendency of patients to bypass PHC facilities disrupts a hospital's core functions and is often linked to the overcrowded outpatient department in these hospitals.

2.2.3 Increased burden of disease

Along with the economic divide investigated in the previous section, another defining characteristic of the public PHC system in South Africa is the considerable array of long-term diseases that providers must treat. This, in turn, minimises the available time allocated to other aspects of PHC, which includes counselling and prevention through education [71]. Communicable diseases like HIV/AIDS and TB are widespread in South Africa, but non-communicable diseases, including hypertension and diabetes, are growing in prevalence [73]. With more chronically-ill patients, public PHC facilities are under significant strain to dedicate more resources to assist all patients.

The most considerable health problem that South Africa faces is the HIV and TB co-infection rate [55]. In 2011, the prevalence of HIV among South Africans aged 15–49 years was 17.3%, which is among the highest in the world [55]. In 2014, TB was ranked as the leading cause of death in South Africa [55]. Additionally, individuals affected by HIV/AIDS are more susceptible to other infections, such as TB, due to their compromised immune systems. In fact, individuals who are HIV positive are ten times more likely to develop TB [105]. Treatment methods for TB exist and are readily available, but require a strict treatment regimen that can last up to six months, and may necessitate multiple visits to a clinic per week [105]. The prolonged period required to treat TB increases the burden of communicable diseases on PHC facilities, and also decreases the likelihood that patients will complete their recommended course of treatment [55].

Statistics South Africa [16] recently released a report on the top ten leading causes of death in South Africa. Although South Africa is afflicted with a high HIV and TB rate, the data provided by Statistics South Africa found that 55.5% of all deaths were attributed to non-communicable diseases, and that diabetes was the second leading cause of death in 2015 after TB [106]. Furthermore, it was reported that diabetes is the number one killer of women living in the Western Cape province [84]. Potential associations between diabetes and TB, as well as HIV, may also further complicate the pattern of increasing diabetes prevalence in South Africa and the challenges posed on resource-constrained health systems. A recent meta-analysis of thirteen studies found that individuals with diabetes were associated with a three-time elevated risk of tuberculosis [49]. Furthermore, the high prevalence of HIV, as well as antiretroviral therapy treatment for HIV, may increase the prevalence of diabetes risk factors and, consequently, diabetes incidence [71].

Although once predominantly regarded as a disease associated with the developed world, it is clear that diabetes now exerts a significant burden in South Africa, which is expected to increase [35]. Many diabetic patients face significant challenges accessing diagnosis and treatment, further contributing to the high mortality and prevalence of diabetic complications [44].

2.3 Diabetes in South Africa

Global projections by the IDF show that diabetes prevalence is expected to double from 285 million in 2010 to 592 million by 2035, with the sub-Saharan African region bearing the greatest burden of this increase, especially in South Africa [72]. Of the 14.7 million people living with diabetes in Africa [47, 85], approximately 11 million are found in sub-Saharan Africa, and 3.91 million live in South Africa. Until recently, diabetes was considered uncommon in these regions, but due to demographic and lifestyle changes, diabetes is increasingly being identified as a prevalent health problem [94].

First, this section firstly provides a brief overview of the diabetes disease. Thereafter, the prevalence of diabetes in South Africa is explored. Consequently, the increasing financial implications of the disease is discussed. Finally, the section concludes with an analysis of the management of diabetes in South Africa.

2.3.1 Diabetes prevalence in South Africa

Type 2 diabetes accounts for 90% of diabetes cases in sub-Saharan Africa, whilst type 1 diabetes and gestational diabetes constitute the remaining 10% [35]. The prevalence of type 2 diabetes has increased significantly from that recorded in pre-1985 surveys conducted within the region. These surveys found that the prevalence for diabetes in sub-Saharan Africa was typically below 1%, where South Africa was often the exception in these studies with a 3.6% diabetic prevalence [35].

Data from the IDF [47] estimates that, as of 2018, 7% of South Africans between the ages of 21–79 years have diabetes. Based on population estimates for South Africa, it is estimated that 3.91 million South Africans in the aforementioned age group have diabetes [47]. Of the 3.91 million people living with diabetes, 61.1% are undiagnosed [102]. Furthermore, it is estimated that an additional 5 million South Africans have pre-diabetes; a condition most likely caused by insulin resistance which results in blood glucose levels being higher than normal, but not significantly high enough to be classified as type 2 diabetes [85]. The highest prevalence of diabetes in South Africa is among the Indian population group with a prevalence of 11–13% [85]. This is followed by 8–10% in the coloured, 5–8% in the black, and 4% in the white population groups [85].

Since diabetic symptoms may initially be extremely mild and develop gradually, combined with an ineffective PHC education intervention system in South Africa, many people fail to recognise symptoms as warning signs of diabetes [85]. In most cases, diabetic complications may have been entirely avoided by early diagnosis and proper treatment [85]. Due to the already considerable burden of disease in South Africa, however, the growing prevalence of diabetes may potentially be unavoidable and lead to increased strain on the already stressed health care system, as well as economic ramifications for South Africa.

2.3.2 Economic implications of diabetes in South Africa

In 2010, the cost per diabetic person in South Africa per annum was approximated by the *Centre for Diabetes and Endocrinology* (CDE) as USD 405.52 [18]. The *Society for Endocrinology, Metabolism and Diabetes of South Africa* (SEMDSA) estimated in 2015 that this cost had risen to USD 918.9 per annum [18]. This observation is consistent with the observed increased prevalence of diabetes in South Africa. As discussed in §2.2.2, the health care spending per capita was equivalent to USD 570, which is significantly lower than South Africa's cost per diabetic person estimated by SEMDSA.

Furthermore, the estimated cost per diabetic person living in South Africa may be significantly lower than the actual cost, due to factors such as undiagnosed, the cost for diabetes prevention programs, over-the-counter medications required for diabetes-related eye and dental problems, and the cost of reduced quality of life, pain, and suffering which cannot be directly measured [81]. The economic implications further extend to the public health care system, which may continue to be overburdened by the potential increase of diabetics who need treatment. With the increasing impact of diabetes which is expected to occur, future health care spending for diabetes is likely to also increase.

2.3.3 Management of diabetes in South Africa

In order to address the increasing financial and economic strain of diabetes in South Africa, the management of the disease must be addressed. In South Africa, there exists a number of private and public agencies, each with a wide spectrum of strategies which could significantly aid the diabetes management problem.

In the private sector, diabetic typically rely on the Centre for Diabetes and Endocrinology—a diabetes management solutions enterprise in South Africa [18]. Their mandate is to improve the health and lives of diabetics by means of various formal diabetes management programmes, partnerships with medical aid schemes, and the education and accreditation of health care professionals in diabetes care principles [18]. Additionally, a non-profit organisation, called Diabetes South Africa was founded to be a support and advocate for all people living with diabetes in South Africa [26]. The Diabetes South Africa primarily lobbys for better facilities, cheaper medication, and better health care services, as well as promoting prevention through public awareness of diabetes, as well as its symptoms and risks [26].

A plethora of private agencies play a role in the management of diabetes in South Africa, the most prominent being the SEMDSA — a scientific society that aims to further the clinical practice, as well as promote both clinical and scientific research publications across all branches of endocrinology, metabolism, and diabetes [102]. This society strives to promote acceptable standards for diabetic training and the professional practice of endocrinology, metabolism, and diabetes, as well as to provide advice (where necessary) regarding the academic standard of individuals and training units [102]. SEMDSA also aims to promote access to the provision of health care services and adequate treatment for all affected diseases with particular focus on the poor and needy [102].

In 2014, SEMDSA collaborated with the South African *Department of Health* (DoH) to produce the updated *Management of type 2 diabetes in adults at primary care level* policy to manage diabetes from a public health care sector perspective [103]. The aim of implementing the updated policy was to reduce diabetic complications and premature diabetic mortality. This formed an integral part of the Diabetes Implementation Strategy for South Africa, which was developed in response to the *African Diabetes Declaration and Strategy* of 2006 [103]. In this policy, diabetes diagnoses, screening, glucose management, comorbidities and complications were addressed [103]. The policy, however, failed to address the treatment of diabetes at a level higher than PHC, as well as the diabetic treatment for children. In 2017, SEMSDA released their 2017 *Guidelines for the management of type 2 diabetes mellitus diabetic* guideline which aimed to inform general patterns of care, to enhance diabetes prevention efforts, and to reduce the burden of diabetic complications in people living with this disease, which was based on international best practice [102]. This guideline addresses diabetes diagnosis, screening, diabetic lifestyle interventions, glucose management, comorbidities, and complications, as well as focusing on special diabetic populations, such as children, adolescents, older persons, and pregnant women [102]. It is, however, noted that this guideline only pertains to the care of adults with type 2 diabetes at primary care level [102].

In the 2013 *Strategic Plan for the Prevention and Control of Non-Communicable Diseases 2013 – 2017*, a listing of all the health care policies published by the DoH since 1998 were presented [104]. Prior to the 2014 *Management of type 2 diabetes in adults at primary care level* policy, only two other diabetic guidelines were listed — the 2005 *Management of diabetes type 1 and type 2 in adults at hospital level* and the 2008 *Guidelines for the management of type 1 diabetes in children* [104]. These two guidelines are, however, not publicly available. Kleinert [58] suggests that the content of South African health policy, as well as the poor documentation and availability thereof, is hampered by ineffective leadership, inexperienced and unaccountable managers, and a weak health system. In addition, both the 2005 *Management of diabetes type 1 and type 2 in adults at hospital level* and the 2008 *Guidelines for the management of type 1 diabetes in children* are only implemented as guidelines, as opposed to explicit policies [104]. The 2014 *Management of type 2 diabetes in adults at primary care level* policy is, therefore, the most recent, publicly available diabetic policy implemented by the DoH at a national level and is, therefore, useful when considering the need to investigate existing policies and intervention strategies to manage diabetes in South Africa. In addition, the SEMDSA 2017 *Guidelines for the management of type 2 diabetes mellitus*, while not published by the DoH, may prove to be useful in understanding the management of diabetes, as it is the most recently published diabetic guideline in South Africa [102]. In order to effectively manage diabetes in South Africa, the public health system should ensure that implemented intervention strategies and policies address the needs of diabetics at all levels of health care.

2.4 Level of analysis

One of the most crucial decisions during any research undertaking is the level of analysis decided upon by the researcher, as it largely dictates the abstraction considered during the research process [7]. In many areas of study, these analysis levels are typically of a hierarchical nature. Since people typically exist within organisational structures, such as schools, families, churches, business organisations, towns, provinces, and countries, hierarchical or nested data structures tend to develop [7].

In order to determine the level of analysis to be used in this research, the use of an hierarchical approach for analysing complex systems is further explored and applied to the hierarchical structure of the diabetic health care system in South Africa.

2.4.1 Hierarchical approach for understanding complex systems

Hierarchy theory proposes that the complexity which exists in a system generally takes the form of modularity in both functionality and structure [157]. In broad terms, modularity is the degree to which the components of a system may be separated and recombined [66]. A hierarchical approach may then be considered as a means of breaking down complexity in a system through a process of discovering or rendering order [157], which allows complex systems to be divided into a smaller set of interrelated systems. A hierarchical perspective may, therefore, be useful in understanding the complexities of a high-level system.

Thomas *et al.* [114] argues that the diabetic health care system in South African is a complex system — characterised by a large number of diverse components, non-linear interactions and dynamic nature. In addition, the diabetic system consists of various interrelated systems, such as the DoH, diabetic policies, medical resources, health care professionals, PHC, the diabetic treatment procedure, and diabetic patients. In order to determine the level of analysis for this research, it is necessary to view the management of diabetic health care in South Africa from an hierarchical perspective so as to identify and better understand the various components of this complex system.

2.4.2 Hierarchical nature of the management of diabetic health care in South Africa

In order to determine the hierarchical nature of the management of diabetic health care system in South Africa, the contents of §2.1–2.3 are used as a basis to provide context and insight to the problem at hand. The general hierarchical perspective considered makes use of three levels: A macro-, meso- and micro-level.

When considering the macro-level perspective of the management of diabetes in South Africa, it is observed that the South African DoH is the most prominent element in this level. Higher levels of the health care system govern the national access to health care, as well as the allocation of total health care expenditure funding, as discussed in §2.2.1. The efficiency of the South African health care system and the inequality between private and public health care, however, prove to be significant challenges for providing adequate diabetic health care, as previously discussed in §2.2.1 and §2.2.2. In addition to the limited total health care expenditure allocation to the public health care system, these challenges, together with the limited health care infrastructure across the country, hampers active change in the management of diabetic health from these higher levels of the health care system. This is consistent with the characteristic of a macro-level top-down approach which allows for slow change and implementation of innovation [13].

The state of the South African DoH and higher levels of government govern how the health care system is able to manage diabetes in South Africa — the management of which is outlined in diabetic policy. As previously discussed in §2.2.3, there are two prominent policies set out the management of diabetes in South Africa: The 2014 South African DoH *Management of type 2 diabetes in adults at primary care level* and the 2017 SEMDSA *Guidelines for the management of type 2 diabetes mellitus diabetic*. These two policies each reside in the meso-level of the management of diabetes within South Africa, and address two different social groups in the health care system. While the SEMDSA policy is aimed at both private and public health care patients, the South African DoH policy is focused exclusively on the patients of the public health care system.

In both of the aforementioned policies, the management of diabetes is outlined to address diagnosis, screening, organisation of care, the diabetic treatment procedure, glucose management, comorbidities, and complications. These policies play a crucial role in how diabetes is managed in the operational PHC and micro-level of the South African health care system. The multitude of PHC facilities across South Africa form part of the micro-level management of diabetes. As discussed in §2.1.3–2.1.5 (with specific focus on §2.1.5) health care professionals in the PHC better understand and experience the practical aspects of diabetic care, as well as the day-to-day management of the disease. Drawing from this experience and understanding what is required on an operational level to manage diabetes, policy on the meso-level can be much better informed. With new innovations for managing diabetes and arising needs from specific PHC units, policy at the meso-level may be amended to improve the management of diabetes for the entire micro-level.

It can be argued that diabetic policy at the meso-level is largely influenced by the South African DoH and higher levels of government at the macro-level, as well as the operational effects of the PHC at the micro-level. Since the macro- and micro-level elements have such a significant effect on the health care policy at the meso-level, it is necessary that the entire South African health care system is considered (from a macroscopic and microscopic perspective) as the level of analysis for this research, as further argued by Thomas *et al.* [114]. This observation also identifies the policy domain as a key area for investigation in the management of diabetes in South Africa.

2.5 Chapter 2 conclusion

In order to highlight the need to investigate existing diabetic intervention and management strategies, in fulfilment of Research Objective I, this chapter first focused on the diabetes disease. Diabetes mellitus was first defined, followed by the classification of the disease according to its clinical stages and aetiological features. The diagnosis and screening of diabetes was then discussed, and the organisation of diabetic care was presented along with associated diabetic complications. The diagnosis and screening of diabetes was then discussed, as well as the diabetic treatment procedure and diabetic complications. A brief overview of the South African health care system was then presented as a mechanism of contextualising the research. The overview focuses on: The efficiency of the system, inequality between the public and private health care system and the increased burden of disease, as well as the increasing diabetic prevalence in South Africa. This was followed by a discussion on the management of diabetes within South Africa, which highlighted the need to address diabetes by employing diabetic management intervention strategies. Focus then subsequently shifted to determining the level of analysis of this research through the analysis the components of the diabetic health care system from a hierarchical perspective. It was shown that health care policy on the meso-level plays a significant role in the management of the diabetes disease in South Africa. Furthermore, since the elements in the macro- and micro-level have a significant effect on the health care policy in the meso-level, it was further suggested that the entire South African health care system should be considered as the level of analysis for this research (from both a macroscopic and microscopic perspective). Finally, the need to investigate the policy domain for the effective management of diabetes in South Africa was evident from the information presented in the chapter. This observation is further investigated in Chapter 3.

CHAPTER 3

Contextualisation of diabetic policy and intervention strategies in South Africa[1]

Contents

This chapter aims to determine if a need exists to investigate alternative intervention strategies for the management of diabetes in South Africa, in fulfilment of Research Objective I. First, the concept of policy is defined from both a public and private health care perspective. Thereafter, various policy analysis methods are introduced and discussed. The focus of this chapter then shifts to global diabetic policy and aims to identify global responses to the diabetes disease, as well as intervention strategies that have successfully managed other NCDs. A systematic review of international diabetic policies is then conducted. The section begins by introducing the methodology of a systematic review, followed by the selection of international policies to investigate based on the WHO diabetic country profiles. A systematic review is then conducted on the selected international diabetic policies to determine the standard of South African diabetic policy in comparison to international diabetic policy, as well as to identify alternative

[1]A significant portion of the text in §3.2 and §3.5 has been reproduced from a conference article that was published as part of this research. The article citation is: Thomas V, de Kock I & Bam L. (2018). "Considering the need for alternative intervention strategies for the management of diabetic policy formulation in South Africa." Proceedings of the *SAIIE29 Conference, 24th –26th of October 2018, Spier, Stellenbosch, South Africa*, pp. 295–306.

diabetic intervention strategies implemented by other countries. Finally, this chapter concludes by analysing South African diabetic policy using appropriate policy analysis methods.

3.1 The definition of policy within a health care paradigm

Policy is commonly thought of as decisions taken or a set of rules developed by those with responsibility for a given domain (*e.g.* the environment, education, trade, or health) [15, 124]. Various authors have, however, proposed subtly different definitions for the term. This may be due to the fact that 'policy' is not a self-evident or precise term [124]. Anderson [3], for example, describes policy as "a purposive course of action followed by an actor or set of actors in dealing with a problem or matter of concern." This policy definition, however, illustrates policy as an *intended* course of action, whereas it may be argued that policies are often the unintended result of many different decisions made over time [15].

Policies are usually defined according to the context in which it is viewed and may be expressed according to a series of instruments, such as practices, regulations, statements and laws [15]. The contents of policies are typically supported (occasionally required) by national and country-specific legislation. The different levels of legislation in South Africa are illustrated in Figure 3.1. Policies may be supported by either mandatory legislation, such as laws, acts and regulations, as shown in the figure, or by voluntary legislation in the form of guidelines and standard operating procedures. Public policies may, therefore, be developed at many levels of authority — in both local or national government. Seiter [98] defines public policy as the conscious attempt of public officials, entrusted with public funds, to achieve specified objectives according to a set of laws, procedures, incentives, and rules.

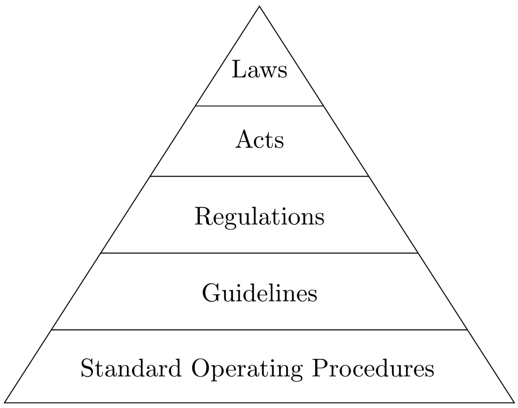


Figure 3.1: *Hierarchical categorisation of legislation in South Africa [15, 117, 124].*

Policies may also be developed from the perspective of the private sector. In the private sector, multi-national companies may introduce policies for all their branches around the world, but authorise local branches to determine their own policies within the framework of the larger established policy. The private sector has to, however, ensure that their private policies are developed within the boundaries of the public laws applicable to a country.

It is worth noting that the term 'health care policy' is discussed, it refers to both public and private policies regarding health. According to Buse [15], health care policy (made in either the public or private sector), is assumed to embrace courses of action (and inaction) which affect the set of organisations, institutions, funding arrangements and services of the health care system.

Since the health of a country's population may be influenced by many factors and influences outside within their health care system, health care policy should consider the actions and effects of organisations external to the health system that have an impact on health (e.g. the tobacco, food or the pharmaceutical industry) [15].

Since there exists a plethora of definition variations of health care policy, there are naturally many ideas as to what health care policy should focus on, and how it should be analysed [124]. An economist, for example, may suggest that the primary purpose of health care policy is to govern the allocation of scarce resources in the health care system; a planner may insist that heath care policy's primary purpose is to influence the determinants of health in order to improve public health [15]; and finally, a health care professional may regard health care policy as being primarily concerned with the operationalisation of health services [124]. For Walt [124], often referred to as the father of policy analysis, health care policy is synonymous with politics and deals explicitly with those who influence policy making, how they exercise that influence, and under what conditions.

3.2 Policy analysis models

According to Walt [124, 125], policy analysis is a multi-disciplinary approach to public policy which aims to explain the interaction between the interests and ideas of the various stakeholders in the policy-making process, and may be a useful tool in understanding past policy failures and successes as well as and planning future policy implementation.

As discussed in §2.4.2, it is crucial that policy and intervention strategies, which ensure effective management of diabetic health care in South Africa, are developed, evaluated and implemented effectively. In order to inform the analysis of South African diabetic policy and intervention strategies in later sections, prominent models of health policy analysis are discussed in this section.

3.2.1 The policy analysis triangle

Walt [124] argues that health policy analysis typically focuses on the content of policy reform and neglects the actors involved in the reform, the processes required to develop and implement change, and the context within which the policy is developed. When a disproportionate amount of focus is placed on the content of a policy, attention is often diverted away from understanding the processes, which supports why may desired policy outcomes fail to materialise [124]. Reich [91] argues that policy reform is generally a political process, which affects the inception, formulation and implementation of policy. Furthermore, policy-makers, whether politicians or bureaucrats, are acutely aware that reforms are often unpopular and may cause significant social instability [124].

From a policy-domain characterised primarily by consensus, health policy is increasingly subject to conflict and uncertainty. This encouraged Walt [124] to generate alternative ways of analysing policy. Walt argues that policy analysis from a systems perspective offers a more comprehensive framework for thinking about health reform than approaches which concentrate on the technical features of the reform's content. Walt, therefore, suggests the use of a simple analytical model to conduct policy analysis, as illustrated in Figure 3.2. This model, commonly referred to as the *policy analysis triangle*, incorporates the concepts of *context*, *process*, *content*, and *actors* to allow policy-makers and researchers to understand the process of health policy reform better, and to plan for a more effective implementation.

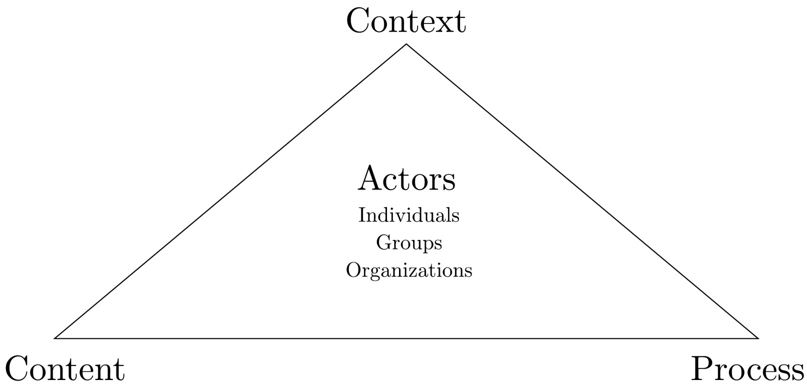


Figure 3.2: *Policy analysis triangle [124].*

The policy analysis triangle is a simplified model of a complex set of interrelationships, which considers the system as a whole, as opposed to considering the context, content, process, or actor entities separately. Actors and stakeholders are terms which are used often interchangeably in policy analysis. Stakeholders, however, do not include actors which may affect or influence a policy decision, but have no stake in the policy or process [15, 63, 124]. The placement of the 'actors' entity in at the center of the policy triangle symbolises the vital need to understand who the actors are and what their role in the policy process is. In addition, Lehmann [63] also defined categories for policy actors, which may either be individuals, groups, or organisations, as opposed to the traditional notion of viewing actors as specific individuals. In terms of the rationale of the policy triangle, it may be observed that actors are influenced by the context within which they live and work. Context may, however, be influenced by either macro- or micro-level factors [63]. In terms of macro-level factors, Leichter [64] proposed that situational, structural, cultural and environmental factors may have an influence on policies, such as instability or uncertainty created by changes in political regime, the economic standpoint of a country, permanent elements or characteristics of a country, social inequalities, historical experiences, or culture. Policy influences on a micro-level, in contrast, refers to the more pressing and local factors which may impact the policy itself or the implementation thereof [63]. Micro-level context includes primarily organisational and local contexts, such as organisational capacity, organisational context and culture, other policies and experiences, and social contexts surrounding the organisation [63].

The process of policy-making is the method in which policies are developed, negotiated, implemented and evaluated, which may be affected by actors and their position in power structures, their own values, and expectations of the policy [15, 63, 124]. The 'process' entity of the policy triangle holds a vital part in policy analysis, as the process of policy-making aides the policy analyst in understanding how the policy was developed and evolved throughout the different policy-making phases, from agenda-setting to implementation and evaluation [124]. The content of policy may, therefore, reflect all of the aforementioned dimensions and consider the other policy analysis triangle entities, from the aim and objectives of the policy to the proposal planned how the implementation of the policy.

3.2.2 Effect-implementation approach to policy analysis

In order to better analyse public policies, Morestin [80] developed the *effect-implementation* analytical framework, which aimed to improve the conditions in which humans live regarding as education, child care, health services and housing [80]. As actors involved in public health typically do not have the power to make public policy decisions, therefore, imperative to consider the public perspective during policy analysis [80]. Given this background, the use of the effect-implementation approach is typically useful when analysing public policies before the decision is made to adopt a policy or when a policy has already been implemented [80]. The former objective aims is to inform the decision maker to promote public adoption of the policy and to compare public polices, while the latter objective aims to evaluate the policy and its public adoption [80].

Morestin [80] based his framework on an evidence-informed approach to decision-making in order to both emphasise the effectiveness of the policies being consider, as well as to understand the issues related to the implementation of the policy [80]. The effect-implementation framework, therefore, analyses two characteristics of a policy simultaneously [80]. In addition, Morestin [80] further breaks down the policy analysis into six analytical dimensions or characteristics: (i) Effectiveness (the ability of a policy to achieve its objective), (ii) unintended effects (outcomes produced through implementation of the policy), (iii) equity (the effect of the policy on different groups, which is based on age, gender, religion, or socio-economic status), (iv) cost, (v) feasibility (analysing the technical aspects and components of which a policy consists), and (vi) acceptability (the judgement of the policy by the public and stakeholders) [80].

The six aforementioned analytical dimensions and characteristics may allow a policy analyst to understand the overall implications of the policy under consideration. The analyst may, however, decide to omit one or more of these dimensions for strategic or practical purposes [80]. After the selected dimensions are identified, it is necessary to locate the information needed for the policy analysis. The results and information found during the data collection phase may then be presented in either a narrative form (a method that relies primarily on the use of words and text to summarise and explain the findings of the synthesis) or as a visual representation in the form of a scorecard [80]. Morestin does, however, suggest that, when conducting the analysis on multiple policies, the scorecard method typically leads to a better overview of the analysis [80].

This effect-implementation analytical framework, therefore, proposes an approach to assist policy analysts in assessing the impact of public policies, policies still to be adopted, and policies that have already been implemented against a set of analytical dimensions, using either the narrative or scorecard method [80]. While this framework is structured in such a way so as to urge analysts to better represent the public perspective to policy-makers [80], it is also flexible enough to be adapted based on the information needs from each context and the resources which are available to conduct the analysis [80].

3.2.3 Advanced analysis methods for policy

Polices are being implemented in systems and environments that are becoming increasingly dynamic and complex [13, 88]. Since the factors surrounding the policy are also becoming more complex, policy analysts are typically more constrained by budgets and time, whilst still needing to deliver adequate policy solutions [13, 86, 88]. As more variables, policy interventions, linear and non-linear interactions, and contextual factors need to be simultaneously be considered during policy analysis, the use of advanced methods during this process are often required [13, 86, 88].

In order to address this increasing complexity in policy analysis, quantitative methods may offer a solution identifying relationships between the design and the outcomes of the policy, critically evaluating the influence that the policy outcomes may have on the political, social and economic factors of a system, and finding alternative solutions and intervention strategies [86, 88]. This systems analysis method (or ‘systems thinking’) is a holistic quantitative approach that investigates the means by which a system's constituent parts interrelate, and how the system works over time and within the context of larger systems [13, 68, 88]. A systems thinking approach investigates complex systems by relying on mathematical approaches to model non-linear and dynamic interactions [13, 68, 88]. Other quantitative methods and techniques used in policy studies include modelling, cost-benefit analysis, risk-benefit analysis, descriptive statistics, operations research and quantification of inputs and outputs [13, 68, 88].

In order to determine the most appropriate quantitative modelling approach for a specific policy analysis, Bellù and Pansini [12], as well as Probst and Bassi [88], suggest that the policy analyst should consider the following requirement specifications:

1. *Problem identification*: The modelling approach assists the analyst in identifying the intervention strategies and actors within the entire system.

2. *Non-linear and dynamic interactions*: The modelling approach accurately investigates the effect of intervention strategies on the system.

3. *Flexibility*: The model adapts well to varied input data, different policy areas and changes to interrelationships.

4. *Data requirements*: When developing a quantitative model, sufficient data is required.

5. *Indication of effect over time*: The model provides the expected outcome of the system over a specified time period in order to model future predictions.

6. *Ease of creation*: Despite the problem complexity, the analyst is able to develop the model using the selected modelling approach and incorporate different policy areas into the model when needed.

Based on the requirement specifications, simulation modelling (which comprises system dynamics, discrete-event and agent-based modelling approaches), is deemed the most appropriate methodology to develop an advanced approach for policy analysis [12, 13, 88, 107]. Using simulation modelling allows for the virtual experimentation of policy scenarios and intervention strategies to determine their comparative effect, cost and impact over any duration of time [13, 88]. In addition, simulation modelling, as an approach for policy analysis, enables an evaluation of the effectiveness and efficiency of policy responses, as well as the unintended consequences of policies, while removing the need for costly trial and error approaches through the use of computer simulation [5, 13, 88, 107].

3.3 Global policy and intervention strategies for diabetes and NCDs

As discussed in §2.1, the prevalence of diabetes continues to increase globally — not only in developed, but also in developing nations. This dilemma has increased pressure on diabetic organisations, national governments, policy-makers and health care systems to improve the management of the disease [134]. Typically, national government, in conjunction with policy-makers, develop diabetic policy according to national health care strategies in order to improve the management of a disease in the health care system, as discussed in §2.3.3. National diabetics policies are, however, generally developed based on international best-standards, diabetic management frameworks, or policies implemented by international diabetic organisations like the WHO [134]. It is, therefore, important to understand existing global responses and diabetic management frameworks in order to better analyse and evaluate South African diabetic policies and intervention strategies.

In addition, diabetes is only one of many non-communicable diseases that has have a considerable impact on mortality rates worldwide [11]. It may, therefore, be useful to investigate intervention strategies which have been successful in managing other non-communicable diseases to reduce their associated mortality rates. Such an approach may lead to the identification of intervention strategies that would not normally be considered within a diabetic context.

This section, therefore, begins by introducing and discussing the diabetic response of the most prominent international health care organisation, namely the WHO, who released a report containing key diabetic policy and intervention strategy recommendations. Thereafter, the intervention strategies which have proven successful in managing mortality rate of other prominent non-communicable diseases, are presented.

3.3.1 The WHO diabetic response

The main function of the WHO is to act as a directing and coordinating authority on international health work, set health care norms and standards, promote and monitor their implementation, ensure valid and productive technical cooperation, and promote research into various health-related areas [136]. It is, therefore, unsurprising that the WHO is regarded as the most prominent body in addressing the prevention and management of diabetes on a global level [136]. The WHO is also the most prominent health care body that has specifically released a report containing key policy and intervention strategy recommendations targeting diabetes. The WHO global report on diabetes is, therefore, significantly important in understanding how South African diabetic policy has been influenced by international diabetic standards and procedures. In addition, the WHO global report on diabetes may also identify alternative diabetic intervention strategies that have not been implemented in the South African context. The WHO global report on diabetes [134] consists of four parts, namely: (i) Global burden of diabetes, (ii) preventing diabetes, (iii) managing diabetes, and (iv) national capacity for prevention and control of diabetes. These four parts of the report are now described in greater detail.

Global burden of diabetes

According to the WHO global report on diabetes [134], there were approximately 422 million people living with diabetes in 2014 globally, in comparison to the 108 million in 1980. In addition, diabetes prevalence has increased faster in low- and middle-income countries than in high income countries [134]. Diabetes resulted in the death of 1.5 million people globally in 2012, and an additional 2.2 million deaths were caused by higher-than-optimal blood glucose, which increased the risks of cardiovascular and other diseases [134]. Of the total 3.7 million deaths, 43% occurred before the age of 70 years. The proportion of deaths as a result of high blood glucose or diabetes (which occurred prior to age 70) is higher in low- and middle-income countries than in high-income countries [134].

Separate global approximations for the diabetes prevalence of type 1 and type 2 do not exist, as advanced laboratory tests are typically required in order to distinguish between these types [134]. The majority of people living with diabetes are, however, affected by type 2 diabetes, which primarily occurs entirely among adults, but is now also more prevalent in children [134].

Diabetes of all types may lead to complications and increase the overall risk of premature death — these risks can, however, be significantly reduced by receiving proper treatment and regular diabetic check-ups [134]. Possible diabetic complications include heart attack, kidney failure, stroke, leg amputation, nerve damage and vision loss [134]. Diabetes, as well as its complications, has significantly affected the economic standing of diabetics and their families, the health care systems, and national economies due to individual medical costs, as well as the loss of work and wages [134].

Preventing diabetes

According to the WHO global report on diabetes [134], diabetes type 1 cannot be prevented at the present time with current knowledge. Type 2 diabetes *can*, however, be prevented through effective approaches, which are also able to prevent the complications and premature death which may result from all types of diabetes [134]. These approaches may lead to good health and a reduced risk of developing diabetes by including policies which target whole populations, as well as those which target people within specific settings, such as in the workplace, at home, or in school [134].

No single policy or intervention strategy can, however, entirely prevent the diabetes disease [134]. Governments and societies are called to consider the health impact of policies in finance, trade, transport, agriculture, urban planning, and education, and that the risk of diabetes is either enhanced or obstructed as a result of policies in these and other sectors [134]. The WHO global report, therefore, recommends the following policy and intervention strategies to prevent diabetes [134]:

- *A life-course approach to preventing diabetes*: Early in life, when physical activity and eating habits are typically formed, there is a significant window for intervention to mitigate the risk of type 2 diabetes and obesity later in life.

- *Supportive environments for physical activity*: The physical environment plays a critical role in facilitating physical activity. Active transport policies and urban planning may encourage walking, cycling and other forms of non-motorised transport. The built environment may also provide recreation, sports, and leisure facilities, ensuring adequate spaces for active living. In addition, the national sports sector may promote regular exercise, especially amongst children and adolescents, which may further strengthen the link between sports, physical activity, and health.

- *Settings-based interventions*: This type of intervention reaches both communities and families in the places where they study, play, work and live to implement both individual and population-wide interventions.

  A school-level approach which focuses on improving both the physical activity and diets of their students may be an effective approach to also improving diet and physical activity patterns outside the school environment. Workplace interventions that address the physical activity and diet of their employees may be effective in addressing health-related behaviours and outcomes. Messages that promote healthy-eating in workplaces and restaurants have, for example, been shown to encourage the consumption of healthier food provided that healthy food items are accessible and affordable as part of the intervention.

- *Fiscal measures for healthy diet*: The cost of healthy food typically prevents people from purchasing and consuming them. Policy action that increases the price of foods that are high in fat, sugar and salt, and increases the accessibility and affordability of healthy foods would likely lead to a decreased consumption of unhealthy food.

- *Trade and agricultural policies which promote healthy diets*: Trade measures may prove effective in reducing the availability of unhealthy foods (and increases the availability of healthy foods), which may lead to the overall improvement of a population's diet.

- *Regulation of marketing of foods high in sugars, fats and salt*: It has been reported that the marketing of foods and non-alcoholic beverages influence children's attitudes, knowledge, and beliefs towards the products. The marketing of unhealthy food choices should, therefore, be limited in order to prevent people from adopting unhealthy eating habits and thus reducing the risk of developing type 2 diabetes later in life. In addition, nutrition labelling is a regulatory tool which may guide and empower consumers towards healthy food choices.

To summarise, the WHO global report's policy and intervention strategies with regards to preventing diabetes, recommends actions that prevent people and children becoming overweight and obese [134] — especially in early childhood. Policies and programmes should be implemented to promote breastfeeding and the consumption of healthy foods, as well as discouraging the consumption of unhealthy foods (e.g. fast food and sugary sodas). Supportive built environments should be constructed to encourage physical activity. Finally, a combination of legislation, fiscal policies and health risk awareness campaigns are great tools to promote healthier diets and physical activity on a public level.

Managing diabetes

According to the WHO global report on diabetes [134], all diabetics are able to live long and healthy lives if their diabetes is diagnosed and managed well, which may be achieved through a series of cost-effective interventions. An early diagnosis is imperative for living a healthy life with diabetes, as the longer a person remains undiagnosed and untreated, the worse their health outcomes typically become.

The effective management of diabetes relies on the accessibility of basic diagnostics (e.g. blood glucose testing) and should, therefore, be available in PHC settings. In addition, well-established systems for referral and back-referral are needed to effectively manage diabetes, since diabetic patients often require regular treatment for complications or specialist assessment [134]. Furthermore, the WHO global report on diabetes urges that diabetics management can be strengthened through the use of effectively implemented standards and protocols and recommends the following policy and intervention strategies to manage diabetes [134]:

- *Screening for early detection and treatment of type 2 diabetes*: There is significant benefit to early detection and treatment, as the reduced lead time between the disease's onset and diagnosis quickens the treatment of the disease, as well as the management thereof to prevent complications. In addition, the current treatment of diabetes does not entirely prevent all complications, but may significantly slow the progress of complications through early interventions.

- *Interventions to promote healthier eating and physical activity*: All diabetics should be encouraged to maintain a healthy diet and regular physical activity. These interventions may include a lower calorie intake for obese and overweight patients, as well as avoiding tobacco use, excessive alcohol consumption, and foods with added sugars. A cost-effective strategy to promote these interventions is the education of patients in groups.

- *Blood glucose control*: The prevention of the development and progression of diabetic complications has been proven in both type 1 and type 2 diabetes when blood glucose control is carefully monitored.
- *Increase the number of human resources*: A range of health professionals are required for the care, treatment and management of diabetes, which includes physicians, dieticians, nurses, and specialists, such as physiotherapists, obstetricians, vascular surgeons and ophthalmologists. A health care system should, therefore, ensure that there are a sufficient number of these health professionals that can treat the diabetic population.
- *Improve access to essential medicines and basic technologies*: Accessibility and availability of essential medicines, such as insulin, and technologies is vital in the role of treating and managing diabetes.

In summary, standardised protocol leads to the improved management of the diabetes disease, which may potentially prevent complications and premature death from the disease using the necessary medicines, patient education to encourage self-care management, interventions that promote healthy lifestyles and regular screening for early detection, and treatment of diabetic complications. In addition, facilities for the management and diagnosis of diabetes should be available and accessible in PHC settings, each with a well-established referral system. Finally, access to essential medicines and technologies should be improved to better manage and treat the diabetes disease.

National capacity for prevention and control of diabetes

According to the WHO global report on diabetes [134], most countries report the implementation of national diabetes policies which aim to reduce the key diabetic risk factors, as well as national guidelines or standards for the improved management of the disease. This is, however, not the case in some lower-income countries, as these policies and guidelines lack funding and implementation. Overall, 47% of countries reported that a national policy or guideline for the management of diabetes has been fully implemented, while 24% of countries report only a partial implementation [134].

Another significant factor to consider for the prevention and control of diabetes is that diabetes management occurs at different levels of the health care system. A referral system enables continuity of care, while ensuring the optimal use of health care services at different levels. According to the WHO global report on diabetes [134], a referral system was reported to be available in 70% of countries, but the full implementation thereof was reported in only 42% of countries.

3.3.2 Intervention strategies for other prominent non-communicable diseases

Of the main types of NCDs, CVDs, chronic respiratory diseases, and diabetes are increasing in prevalence together with having continued growth in mortality rates [135]. According to the National Cancer Institute of the USA [83], the only NCD decreasing in prevalence is cancer — specifically lung, colon, prostate and breast cancer [83].

It is widely acknowledged that deaths related to breast cancer have decreased globally over the past few decades [20, 23, 82], with rates declining approximately 40% between 1989 and 2015 [74]. According to De Santis [23], the reduction in breast-cancer mortality is as a result of improvements in both treatments and early detection using mammography. The screening and early detection through breast examinations and mammograms (which is now considered to be a vital component of any medical health care insurance coverage) has led to the significant reduction in breast cancer mortality rates [23, 82].

While it is still a concerning disease that afflicts many, breast cancer is not the result of poor lifestyle choices. This, however, cannot be said in the case of lung cancer, where smoking of tobacco is a primary cause of the disease. The mortality rate for lung cancer has decreased by 29.3% from 2005 to 2013 [83], which is likely due to the considerable reduction in tobacco smoking over the last two decades — a fact that highlights the success of tobacco control interventions through education and marketing strategies [48]. It is, therefore, interesting to note that both the decreases in the number of breast cancer and lung cancer deaths may be largely attributed to proactive intervention strategies, such as early detection though screening and preventative education, as opposed to reactive policies.

3.4 Systematic review of international diabetic policy

As described in §2.4.2, two prominent policies exist for managing type 2 diabetes at a primary health care level in South Africa: (i) the 2017 SEMDSA *Guidelines for the management of type 2 diabetes mellitus diabetic* guideline and (ii) the 2017 South African DoH *Management of type 2 diabetes in adults at primary care level* policy.

In order to evaluate the content of these two policies, it is first necessary to determine whether the policies meet international best practice. A comparison of the two South African policies with diabetic policies from other countries is, therefore, conducted in the form of a systematic review analysis.

This section begins by introducing the methodology of a systematic review, as well as the steps required to perform a systematic review. Thereafter, diabetic policies from various countries worldwide are selected for review according to a set of later established criteria. Finally, this section presents the systematic review conducted on the two aforementioned diabetic policies from South Africa, as well as those from around the world.

3.4.1 Methodology of a systematic review

Oakley and Fullerton [6] define the systematic review as "a review of a clearly formulated question that uses systematic and explicit methods to identify, select and critically appraise relevant research, and to collect and analyse data from the studies that are included in the review." In addition, such a review is systematic in its attempts to locate both published and unpublished research, and to critically evaluate the research on grounds of relevancy to the study, as well as according to a predetermined set of methodological criteria [6]. Only the research that is found to both fulfil the methodological criteria and be relevant to the review question is combined into the final research analysis. The systematic review also combines the results of these research studies and, therefore, provides a summary of the 'best available evidence' related to a given question [6].

According to Oakley and Fullerton [6], there are definite advantages to conducting systematic reviews of a high quality. The first being that time and labour resources are saved, which enables reviewers to inform or respond to developments in policy and practice in a time-appropriate manner. A systematic review may also reveal knowledge gaps that call for more research, and how well research findings can be applied to everyday practice. In addition, the conclusions of systematic reviews are more reliable than those of individual studies, as the consultation of a systematic review removes the need to understand the individual differences between the results of the various items of research.

A high quality systematic review typically follows a procedure that begins with the formulation of a clear and precise research question, which includes a definition of the participants, the interventions to be assessed, and the outcomes to be measured by the review [6, 19, 40]. A protocol is then developed which outlines the inclusion and exclusion criteria and the sources to be considered. A thorough literature search is then conducted, which combines the results obtained through electronic database searches and searching the references of identified studies [6]. Research studies are selected for review if strict inclusion criteria are met. Appropriate data are extracted from the included studies using standardised criteria and procedures. The results of the studies are then synthesised using narrative synthesis which take into account study designs [6, 19, 40]. Perhaps the most significant step of the systematic review procedure is the interpretation and reflection of the synthesised results in terms of the research, policy and practice implications. The final step of a systematic review typically involves the writing up and publication of the synthesised results thus ensuring that the methodology of the review is clearly defined and the limitations of the included research studies, as well as the systematic review itself, are acknowledged [6].

3.4.2 Identification of international diabetes policies

According to the systematic review methodology presented in the preceding subsection, the first step in conducting a systematic review is to formulate a precise research question. The eventual aim of this chapter is to evaluate the content of two available South African diabetic policies: The 2017 SEMDSA *Guidelines for the management of type 2 diabetes mellitus diabetic* guideline and the 2017 South African DoH *management of type 2 diabetes in adults at primary care level* policy. In order to do so, it is first necessary to first determine whether these South African diabetic policies meet international best practice. The research question posed is, therefore, to determine where the two aforementioned South African diabetic policies are in agreement with international best practices.

In order to explore a wide array of varying international diabetic policies, countries with the highest and lowest prevalence for diabetes worldwide are considered in this systematic review. In addition, a significant focus is placed on identifying both developed and developing countries so as to ensure a broadened scope of available alternative intervention strategies. The twenty-one countries identified (including South Africa) are listed in Table 3.1 according to descending diabetic prevalence.

Further summarised in Table 3.1 are details from the WHO diabetes profile for each country (if available). An extract from the WHO diabetes profile for South Africa is shown in Table 3.2 to illustrate the WHO diabetes profiles of a country, as well as to further describe the diabetic standing in South Africa [152]. In this WHO diabetes profile, it is shown whether a specific country has an operational policy, strategy, or action plan for diabetes, as well as whether there are published evidence-based national diabetes guidelines, protocols, or standards. Another aspect considered in the WHO diabetes profile is whether the specific country had a diabetes registry — an intervention strategy perhaps not well-known in South Africa, as it has not been

TABLE 3.1: *Selection of countries to be included in a systematic review of diabetic policies.*

Country	Status of development	Diabetic prevalence percentage of total country population	WHO diabetes country profile availability	Operational policy, strategy, or action plan for diabetes	Evidence-based national diabetes guidelines, protocols, or standards	Diabetes registry	Availability of resources and technology	Availability of country diabetes policy
Nauru	Developing	24.1	Yes [150]	Yes	Do not know	Yes	Not generally available	No
Tuvalu	Developing	23.1	Yes [155]	No	Available and fully implemented	No	Not generally available	No
Marshall Islands	Developing	20.7	Yes [149]	Yes	Available and fully implemented, but documentation not provided		Generally available	Yes [4]
United States of America	Develped	11	Yes [154]	Yes	Do not know	No	Generally available	Yes (Only private policy) [2]
China	Develped	10.9	Yes [140]	Yes	Available and fully implemented	Yes	Generally available	No
Singapore	Develped	10.5	Yes [151]	Yes	Available and fully implemented	No	Generally available	No
Malta	Develped	10	Yes [148]	Yes	Not available	Yes	Generally available	Yes [25]
India	Developing	9	Yes [144]	Yes	Available and partially implemented	Yes	Generally available	No
United Kingdom	Develped	7.7	Yes [153]	Yes	Available and fully implemented	Yes	Generally available	Yes [118]
Australia	Develped	7.3	Yes [137]	Yes	Available and fully implemented	Yes	Generally available	Yes [113]
Canada	Develped	7.2	Yes [139]	Yes	Available and fully implemented	Yes	Generally available	Yes [24]
South Africa	Developing	7	Yes [152]	Yes	Available and fully implemented, but documentation not provided	No	Not generally available	Yes (Public and private policy) [102, 103]
Lithuania	Develped	4	Yes [146]	Yes	Available and fully implemented, but documentation not provided	No	Not generally available	No
Estonia	Develped	4	Yes [142]	No	Available and fully implemented	No	Not generally available	No
Ireland	Develped	4	Yes [145]	Yes	Available and fully implemented	No	Generally available	Yes [36]
Gambia	Developing	2	Yes [143]	No	Not available	No	Not generally available	No
Mali	Developing	1.6	Yes [147]	Yes	Available and fully implemented	Yes	Not generally available	No
Benin	Developing	1.5	Yes [138]	Yes	Available and partially implemented	No	Not generally available	No

TABLE 3.2: *Extract of South African National response to diabetes from the WHO Diabetic Profile on South Africa.*

Policies, guidelines and monitoring	
Operational policy/strategy/action plan for diabetes	Yes
Operational policy/strategy/action plan to reduce overweight and obesity	Yes
Operational policy/strategy/action plan to reduce physical inactivity	Yes
Evidence-based national diabetes guidelines/protocols/standards	Available and fully implemented, but documentation not provided
Standard criteria for referral of patients from primary care to higher level of care	Available and fully implemented
Diabetes registry	No
Recent national risk factor survey in which blood glucose was measured	Yes

Availability of medicines, basic technologies and procedures in the public health sector			
Medicines in primary care facilities		*Basic technologies in primary care facilities*	
Insulin	Generally available	Blood glucose measurement	Generally available
Metformin	Generally available	Oral glucose tolerance test	Generally available
Sulphonylurea	Not generally available	HbA1c test	Not generally available
Procedures		Dilated fundus examination	Not generally available
Retinal photocoagulation	Generally available	Foot vibration perception by tuning fork	Not generally available
Renal replacement therapy by dialysis	Not generally available	Foot vascular status by Doppler	Not generally available
Renal replacement therapy by transplantation	Not generally available	Urine strips for glucose and ketone measurement	Generally available

implemented. Finally, the WHO diabetes profile states whether the technological and medical resources needed to diagnose and treat diabetes are generally available.

As may be seen in Table 3.1, Nauru, a developing country, has the highest prevalence (24.1% among the population aged 20-79 years) of diabetes worldwide [150]. Two other countries also in Oceania, Tuvalu and Marshall Islands, follow Nauru as the second and third highest prevalence of diabetes, respectively [149, 155]. Although there is a significantly higher genetic susceptibility to the development of type 2 diabetes amongst the Oceania population, according to the WHO [45], the countries in Oceania likely have significantly high rates of diabetes due to the populations shifting away from a diet rich in home-grown, local food towards a more Westernised diet consisting primarily of processed foods [120].

The fourth highest in diabetic prevalence worldwide is the USA, having the highest prevalence (11% of the population aged 20-79 years) of diabetes among all developed nations [154]. China is a close second to the USA (10.9%) [140] in terms of diabetic prevalence in developed nations, followed by Singapore (10.5%) [151] and Malta (10%) [148]. The developed countries with the lowest estimated prevalence for diabetes are Estonia, Lithuania, and Ireland (each with approximately 4% prevalence) [142, 145, 146], followed by Denmark (5.7%) [141], Canada (7.2%) [139], Australia (7.3%) [137], and the United Kingdom (7.7%) [153], as shown in Table 3.1. It is perhaps surprising to note that South Africa, a developing country with a 7% prevalence for diabetes, is surrounded by many developed countries with relatively the low diabetic prevalence.

The ten countries with the lowest estimated diabetic prevalence worldwide are all found in the African continent, which may be partly attributed to the higher prevalence of other diseases and the lower life expectancy in the region [67]. It is, however, estimated that the diabetic prevalence rates in Africa are expected to double by 2040 [67]. Benin (1.5%) [138], Mali (6.9%) [147] and the Gambia (2%) [143] are the countries with the first, second and third lowest diabetic prevalence worldwide. The low prevalence of diabetes in these countries is not attributed to diabetic intervention strategies or polices, but rather to the premature mortality caused by diseases, such as malaria and HIV/AIDS as well as other factors including malnutrition and low birth weights [67].

From the identified countries, only nine of the countries' diabetic policies (including South Africa) were found to be publicly available, as may be seen in Table 3.1. The USA is an interesting case. While each state in the country generally has its own diabetic policy, no national policy has been implemented. There is, however, a private diabetic policy implemented by the *American Diabetes Association* (ADA) that addresses standards of diabetic care at a national level [2]. Since the composition of the ADA diabetic policy is similar to that of the private diabetic policy introduced by SEMDSA in South Africa, the ADA diabetic policy may be a useful addition to the systematic review to provide a comparison point for South Africa's own private policy. Based on the availability of each country's diabetic policy, the systematic review of international diabetic policies considers national diabetic policies from Australia, Canada, Denmark, Ireland, Malta, Marshall Islands, South Africa, and the United Kingdom, as well as private diabetic polices from South Africa and the USA.

3.4.3 Systematic review of international diabetes policies

A systematic review was conducted on the diabetic policies of the countries identified in §3.4.2 so as to determine whether South African diabetic policy met international practices. The systematic review investigated the content of the diabetic policies from the aforementioned countries and considered whether various criteria and policy elements were addressed in each policy document. These criteria and policy elements investigated in the systematic review, were identified from the WHO global report on diabetes. Throughout the process of reviewing the various international diabetic polices, appropriate criteria were also systematically appended to the review. The systematic review of diabetic policies is presented in Table 3.3.

The most notable diabetic intervention strategy observed throughout the systematic review was that of the diabetes registry. A diabetes registry ensures the provision of quality diabetes health care by means of improved processes of care [36]. The registry shares patient information between the primary care and higher care levels for the benefit of the patient, and to expedite and facilitate integrated care [36]. Such a registry may ensure the collection of data, from local to national health care levels, to allow for the planning of medical resource and technology allocation [36]. The registry may typically contain the patient's details, type of diabetes or related hyperglycaemic condition, and other details related to such as diabetic complications. In 2003, a diabetes registry was implemented in Denmark [110]. The initial objective of the Danish Adult Diabetes Registry was to collect data from the primary and secondary health care facilities to determine and evaluate the quality of the treatment provided to diabetic patients [51]. During the first three years of the registry's implementation, the diabetes mortality rate in Denmark decreased by 40% [17]. According to Jorgensen, the diabetes registry database in now considered a significant component in ensuring the quality of diabetes treatment and management in Denmark's health care system [51].

A summary of the systematic review, as well as the diabetic prevalence of each country is shown in Table 3.4. As may be seen in the summary, the relationship between the content addressed in a country's diabetic policy and the prevalence of diabetes, as well as the number of diabetics in a country, is not directly proportional. In fact, the correlation between the number of policy criteria addressed in a country's diabetic policy and the prevalence of diabetes is 0.0176, and a correlation of 0.2263 is observed between the number of policy criteria addressed in a country's diabetic policy and the number of diabetics in each country, which indicates a weak relationship between these attributes [62]. This may be further demonstrated in the case of the USA. Despite the ADA policy addressing the most policy criteria in the systematic review, as shown in Table 3.4, the USA is the developing nation with the highest prevalence of diabetes, as presented in Table 3.3. This weak relationship between the content of a diabetic policy and the prevalence of diabetes further validates Walt's argument (presented in §3.2.1) that a significant focus on the policy content (and not policy context, actors and process elements) can lead to poor policy implementation and outcomes.

Table 3.3: *Systematic review of international diabetic polices.*

	Australia	**Canada**	**Denmark**	**Ireland**	**Malta**	**Marshall Islands**	**South Africa: Private policy**	**South Africa: Public policy**	**United Kingdom**	**USA: Private policy**
DEFINITION, SYMPTOMS, DIAGNOSIS, SCREENING, ORGANIZATION OF DIABETES CARE										
Definition and classification of diabetes mellitus	X	X	X	X	X	X	X	X	X	X
Symptoms of type 2 diabetes	X	X		X	X	X	X	X	X	X
Diagnosis of type 2 diabetes	X	X	X	X	X	X	X	X	X	X
Screening for early detection of type 2 diabetes	X	X	X	X		X	X	X	X	X
Organization of diabetes care	X	X	X	X	X	X	X	X	X	
Requirements at clinic level for a diabetes service	X			X		X		X		
Schedule of visits to a diabetes clinic	X			X		X		X		X
Preventing type 2 diabetes	X		X	X	X	X	X	X	X	X
MANAGEMENT OF BLOOD GLUCOSE										
Targets for glycaemic control	X	X	X	X		X	X	X		X
Glycaemic management	X	X	X	X	X	X		X	X	X
Sick days	X			X	X			X		
Follow-up	X	X		X	X	X		X	X	X
Referrals	X			X	X			X		X
Hypoglycaemia	X	X	X	X	X	X	X	X	X	X
Hyperglycaemic emergencies	X	X		X	X	X	X	X	X	
In-hospital management of hyperglycaemia		X					X			
Diabetes Register		X	X	X						
LIFESTYLE INTERVENTIONS										
Self monitoring of blood glucose	X	X	X	X		X	X	X	X	X
Nutrition therapy	X	X	X	X	X	X	X	X	X	X
Physical activity	X	X	X	X	X	X	X	X	X	X
Tobacco use	X	X	X	X	X	X		X	X	X
Alcohol consumption	X		X	X		X		X	X	X
MANAGEMENT OF CO-MORBIDITIES AND COMPLICATIONS IN PATIENTS WITH DIABETES										
Obesity	X	X	X		X	X	X	X	X	X
Cardiovascular risk and dyslipidaemia	X	X	X	X	X	X	X	X	X	X
Aspirin or anti-platelet therapy		X	X	X		X	X	X	X	X
Hypertension	X	X	X	X		X	X	X	X	X
Diabetic kidney disease	X	X	X	X	X	X	X	X	X	X
Diabetic eye disease	X	X	X	X	X	X	X	X	X	X
Diabetic foot problems	X	X	X	X	X	X	X	X	X	X
Neuropathy	X	X	X	X	X	X		X	X	X
DIABETES CARE IN SPECIFIC POPULATIONS										
Diabetes care in pregnancy	X	X		X	X	X	X	X	X	X
Family planning and pre-conception care	X			X				X		X
Type 2 diabetes in older persons		X			X	X	X	X		X
Type 2 diabetes in children and adolescents		X			X	X	X			X
High risk ethnic groups	X	X	X	X		X		X		X
Type 2 diabetes and HIV							X	X		X
Prevention or delay of type 2 diabetes	X	X	X	X	X	X	X	X	X	X
Type 2 diabetes and driving	X	X		X			X	X		X
Periodontal disease	X	X						X		X
Female sexual dysfunction	X									X
Male sexual dysfunction	X	X	X	X			X			X
Type 2 diabetes and mental health		X			X					X
Total count	35	33	25	34	25	31	27	36	25	36

Table 3.4: *Summary of systematic review and diabetic prevalence of each country.*

Country	Number of policy criterion met in systematic review	Diabetes prevalence	Number of diabetics in population
USA: Private policy	36	11%	3582700
South Africa: Public policy	36	7%	3335136
Australia	35	7%	1752000
Ireland	34	4%	191360
Canada	33	7%	2643120
Marshall Islands	31	21%	10997
South Africa: Private policy	27	7%	635264
Denmark	25	6%	328890
Malta	25	10%	46030
United Kingdom	25	8%	5083540

A notable observation is that, despite the growing prevalence of diabetes in South Africa, the national South African diabetic policy met the highest number of policy criteria (tied with the USA) in the systematic review shown in Table 3.4. As the national South African diabetic policy already addresses a considerable number of key diabetic policy elements and criteria, the further improvement of the policy content may likely not act as a suitable intervention strategy for decreasing the prevalence of diabetes in South Africa. In order to identify the intervention strategies needed to more effectively manage diabetes in South Africa, it is necessary to perform a detailed policy analysis on South African diabetic policy.

3.5 Analysis of South African diabetic policy and intervention strategies

During the discussion of the systematic review in the preceding section, it was determined that, in order to further evaluate the content and influence of the South African policies, as well as to identify the intervention strategies needed to more effectively manage diabetes in South Africa, it may be necessary to perform a detailed policy analysis on South African diabetic policy. As discussed in §3.2, there exists policy analysis methods to effectively analyse the South African diabetic policy. It was argued in §2.4.2 that diabetic health care in South Africa should be considered from a systems perspective due to the complex nature of the system resulting from dynamics and non-linear interactions. It, therefore, seems appropriate to employ the policy analysis triangle to analyse the South African diabetes policy [114], as this approach is most effective in analysing policy from a systems perspective with complex interactions, as discussed in §3.2.1. Both the 2014 *Management of type 2 diabetes in adults at primary care level* policy published by the South African DoH and the SEMDSA 2017 *Guidelines for the management of type 2 diabetes mellitus diabetic* guideline published by SEMDSA, are evaluated in order to identify intervention strategies that could contribute to more effectively managing diabetes in South Africa.

The policy analysis begins by considering the actors involved in both policies. In the context of the national diabetic policy, it is observed that the policy was developed by the South African DoH with advice and direction provided by the SEMDSA Steering Committee and the Advisory Committee [102]. It is, however, noted that, while these actors (the DoH and SEMDSA subject-matter experts) were acknowledged for their contribution to the policy, the consultation of diabetic patients, PHC clinicians, and community health workers were not mentioned. Public policy is, however, typically created in an open environment with free debate subject to the force of law, whereas private organisations, such as SEMDSA, may develop their own policy based on the rules and regulations of their organisation without public accountability. This characteristic of private policy should also be considered when analysing the SEMDSA policy [114]. While the content of the SEMDSA policy is based on international best-practice and the actors involved include the guideline committee (consisting of an extensive number of subject-matter experts), the public were also not acknowledged as actors in the policy-making process. Since there were a significant number of subject-matter experts involved in the creation of both policies, as well as an external moderation process, the content of both policies may be considered of a significantly high quality that meets international best-practice, as further confirmed by the results of the systematic review in §3.4.3. It is, however, noted that the content of both policies is directed at adults with type 2 diabetes at primary care level, and do not address higher levels of health care or other types of diabetes.

While analysing the actors involved, it is observed that diabetic patients, PHC clinicians, and community health workers were not actively involved in the policy-making process. The knowledge of the involvement of actors is vital when the context of a policy is considered. As described in §2.2.2 and §2.2.3, there is a large inequality between the private and public health care sector, and an increased burden of disease in South Africa. This has placed a significant burden on the PHC clinicians and community health workers and, therefore, prevents diabetics from easily accessing sufficient health care. In addition, the referral system in South Africa (which is poorly utilised as discussed in §2.2.3), is extensively relied upon in the public policy. Although the content of both policies should equip PHC clinicians to treat diabetics effectively, the context of the current South African health care system prevents PHC clinicians from providing sufficient health care to diabetics [114]. Finally, the process aspect of the policy analysis is considered. While the South African DoH released and implemented the *Management of type 2 diabetes in adults at primary care level* policy in 2014 to manage diabetes in South Africa, the prevalence of the disease has significantly increased, as discussed in §2.3.1. This fact is also true for the SEMDSA policy.

The triangle policy analysis, therefore, reveals that, while significant focus is placed on the content of both diabetic policies, the context, process and actors were largely not considered in the policy-making process [114]. Although the policy analysis triangle is a suitable approach for providing a high-level overview analysis of the policies, a more comprehensive and detailed understanding of the South African diabetic policies may be achieved through an advanced policy analysis method. For the successful completion of the research objectives of this study, it is necessary to employ a more advanced modelling approach for policy analysis, such as a modelling approach so as to obtain a deeper and more dynamic understanding of the South African diabetic policies, as suggested in §3.2.3.

3.6 Chapter 3 conclusion

Chapter 3 aimed to determine if a need exists to investigate existing intervention strategies for the management of diabetes South Africa, in fulfilment of Research Objective I. After having defined policy within both a public and private health care context, as well as introducing various policy analysis methods, global responses to the diabetes disease were identified. A systematic review of international diabetic policies was consequently conducted so as to determine the standard of South African diabetic policy in comparison to international diabetic policy. It was found that a weak relationship exists between the content addressed in a diabetic policy and the diabetic prevalence is a country. As the South African diabetic policy met the highest number of criteria in terms of content addressed in the policy, it was, therefore, determined that improving the content of the diabetic policy would not act as a suitable intervention strategy to more effectively management diabetes in South Africa. It was then suggested that a more detailed policy analysis should be conducted on South African diabetic policy.

The policy triangle analysis was then used to analyse South African diabetic policy. The analysis determined that significant focus is placed on the content of the policy, and that the context, process and actors were largely omitted in the South African diabetic policy-making process. It was, therefore, determined that there is a need to investigate existing intervention strategies for the management of diabetes in South Africa. The policy analysis triangle is, however, limited to providing only a high-level overview of the policy during analysis. Finally, it was argued that, in order to obtain a more detailed understanding of the South African diabetic policies, it may be appropriate to use a more advanced policy analysis approach, such as modelling. This argument is further investigated in Chapter 4.

CHAPTER 4

Contextualisation of modelling approaches[1]

Contents

At the onset of this chapter, a set of requirement specifications are developed, in fulfilment of Research Objective II, to determine an appropriate method for investigating existing intervention strategies for the management of diabetes in South Africa. Thereafter, modelling approaches of a general nature are discussed and presented, which is followed by a detailed description of the most notable modelling approaches. The set of requirement specifications are then used to evaluate the aforementioned modelling approaches in order to identify the most appropriate approach to model the dynamics of diabetic health care in South Africa with the purpose of investigating existing intervention strategies for the management of diabetes, in fulfilment of Research Objective III. Finally, the identified modelling approach is discussed in detail.

4.1 Development of requirement specifications

In order to identify the most appropriate modelling approach to investigate the South African diabetic policies and diabetic health care, a set of requirement specifications need to be developed. From the triangle policy analysis conducted in §3.5, as well as drawing upon the work

[1] A significant portion of the text in §4.1 and §4.2 has been reproduced from a conference article which was published as part of this research. The article citation is: Thomas V, de Kock I & Bam L. (2018). "Considering the need for alternative intervention strategies for the management of diabetic policy formulation in South Africa." Proceedings of the *SAIIE29 Conference, 24th–26th of October 2018, Spier, Stellenbosch, South Africa*, pp. 295–306.

of Bellù and Pansini [12] and Thomas *et al.* [114], the following requirement specifications are established in order to investigate intervention strategies for the management of diabetes in South Africa by means of a modelling approach:

1. *Problem identification*: The modelling approach assists the analyst in identifying the intervention strategies and actors within the entire diabetic health care system from a level of abstraction appropriate to the system.

2. *Non-linear and dynamic interactions*: The modelling approach accurately investigates the influencing and causal factors that affect of outcomes of the intervention strategies on the health care system, as well as on the diabetic and non-diabetic populations.

3. *Flexibility*: The model adapts well to varied input data, different policy areas and changes to interrelationships in the model.

4. *Data requirements*: When developing a quantitative model, an appropiate set of data is almost always required. The modelling approach should, however, be capable of investigating diabetic intervention strategies when the data is available.

5. *Indication of effect over time*: The model provides the expected outcome of the diabetic health care system over a specified time period in order to model future predictions.

6. *Ease of creation*: Despite the problem complexity, the analyst is able to develop the model using the selected modelling approach and incorporate different policy specifications into the model when needed.

These requirement specifications serve at the basis for evaluating the various modelling approaches for modelling the dynamics of diabetic health care in South Africa with the purpose of investigating existing intervention strategies for the management of diabetes.

4.2 Modelling approaches

Modelling is an approach used to solve problems in the real-world [13]. Often, the solutions to problems cannot be determined by experimenting with the real-world system, owing to the high cost implications of disrupting such a system, building new infrastructure, implementation changes, or, in some cases, the non-existence of the system [13]. In order to overcome these constraints, a model of the real-world system is often built and represented using a specialised modelling language. Upon completion of the model's construction, and typically throughout the model-building process, the real-world system is thoroughly explored and analysed so as to comprehend its structure and behaviour. This ensures noteworthy real-world system aspects have been effectively replicated in the associated model [13]. When a high-quality solution has been reached, the proposed changes may be implemented into the real-world system, or the system construction commences.

One of the more standard modelling approaches is that of a computer model, whereby standard software packages are employed. Microsoft Excel is one of the most popular modelling softwares, as it is readily available and is fairly simple to use [13]. This software allows for the construction of a model which is capable of accepting one or more sets of input variables and returning a corresponding set of output variables. The sets of inputs are linked to the output values *via* chains and scripts. This type of model is commonly referred to as an analytical model and is characterised by possessing no memory, as well as being linear and time-independent [13]. It may, however, become complex (if not impossible) to derive a formula in some model formulations should the problem require some measure of memory, as well as present non-linear behaviour and non-intuitive influences between its variables.

Complex, dynamic systems typically present multiple non-linear interactions, and may act as barriers to solving problems using analytical approaches. In order to address the issues that arise in complex systems, Banks [8] recommends that a mathematical computational method, based on iterative algorithms, should be employed, and identifies simulation modelling as the most appropriate method for analysing and understanding such systems. According to Smith [101], simulation modelling may be regarded as the process of designing a model of a real or imagined system and conducting experiments using this model. Simulation models are built using specialised simulation software tools, which typically require significant training to use them effectively [8, 13]. Banks [8] suggests that the purpose of simulation modelling is to better understand the behaviour of the real-world system [8], and allows for the evaluation and analysis of the effects of new system designs, modifications, or proposed changes to an existing system and its operations beyond that of the available data for time or space [8, 101]. It is further postulated by both Banks [8] and Borschev [13] that simulation modelling is the only practical means to test complex system models, and that without simulation, even the best conceptual models may only be tested and improved by relying on the learning feedback through the real-world. This real-world feedback is, however, slow and is often rendered ineffective by dynamic complexity, time delay, inadequate or ambiguous feedback, poor reasoning skills, or the cost of experimentation [8, 13]. In these circumstances, simulation modelling becomes one of the only reliable ways to test hypotheses and evaluate the likely effects of existing strategies or interventions, such as those in policy [8, 101, 107].

According to Banks [8] and Borschev [13], the three most notable and commonly employed simulation modelling approaches are *system dynamics* modelling, *discrete-event* modelling, and *agent-based modelling*. In the section to follow, these simulation modelling approaches are introduced and discussed in greater detail.

4.2.1 System dynamics modelling

System dynamics is a simulation method first developed in the 1950s by MIT Professor, Jay Forrester [13, 107]. Forrester used the laws of physics, with a particular reference to the laws of electronic circuits, to examine and characterise the dynamics of economic, as well as social structures [13, 107].

According to Pruyt [89], system dynamics is "a method to describe, model, simulate and analyse dynamically complex issues and/or systems in terms of the processes, information, organisational boundaries and strategies". This view is achieved by modelling the system as a causally closed structure which, in turn, defines the system's behaviour [13, 107]. Since feedback loops act as the heart of a system dynamics model [13], it is imperative to identify the various feedback loops within the system. In this approach, all elements and concepts in the real system are defined as continuous quantities — interconnected in loops of information feedback and circular causality to demonstrate the dynamic linear and non-linear interactions of the system [107]. Furthermore, the system dynamics approach involves identifying various accumulations in the model, as well as their inflow and outflow rates [13, 107].

Another element to consider when selecting a system dynamics approach is that the observed system is typically modelled at a high level of abstraction [13, 107]. This method, therefore, considers the entire perspective, and disregards negligible details and dependencies which do not play a critical role in the outcome of the model. The system dynamics approach develops a model from a top-down perspective, and relys on notions that often do not have direct material or measurable equivalents in the real-world system (e.g. morale, awareness, and knowledge) [13, 107]. The selection of these notions, as well as the creation of the corresponding feedback structures, are typically not as clear-cut as the design of a process flowchart or agent behaviour as in the case of other methods of simulation development.

4.2.2 Discrete-event modelling

Discrete-event systems are systems where specific state changes or events occur at discrete instances, in time and where no state change takes place in the system between these events; the use of discrete-event modelling is appropriate for such systems [13, 101]. This form of modelling, developed by IBM engineer Geoffrey Gordon in the 1960s, allows the simulation developer to model the system as a process (or a sequence of operations) performed across entities [13, 121], where operations include delays, services, and decisions surrounding the selection of a process branch [13, 101, 121].

Discrete-event modelling is typically used for models where multiple entities compete for a limited number of resources, and is best suited for modelling queuing systems and supply chains [101]. The system is commonly modelled using a process flowchart. The flowchart begins with a 'source' block, that generates entities entering the system, and ends with a 'sink' block which terminates the entities from the model. The entities pass through various processes stipulated by the flowchart imposed by the model [13]. Since discrete-event models are stochastic (due to the input data typically being drawn from a probability distribution), the model should be executed for a specified period of time or a specified number of repetitions, so as to produce a statistically valid and reliable output [13, 101].

According to Borshchev [13], the level of abstraction suggested for discrete event modelling is significantly lower than that of the system dynamics modelling approach. The difference lies in the fact that, in system dynamics, individual objects are aggregated, while in discrete-event modelling, each object in the system is represented as an entity or a resource unit. A higher level of detail is, therefore, necessary in a discrete-event modelling setting. A final consideration with regard to discrete-event modelling is the fact that that both entities and resources units are of a passive nature, free of any intrinsic 'behaviour' [13]. The only events or occurrences to take place in discrete-event models are defined by the process flowchart. This fact is the most notable difference between discrete-event modelling and agent-based modelling [13].

4.2.3 Agent-based modelling

Agent-based modelling is a modelling approach developed in the early 2000s as a result of the advances in modelling technology, namely object-orientated modelling and state charts, together with a rapid growth of available CPU power and memory [8]. This is in the light of the fact that agent-based models are typically more computationally demanding than both system dynamics and discrete event models [13]. Additionally, the development of agent-based modelling was also triggered by the pursuit of reaching a deeper insight into systems not often achieved by traditional modelling practices [8, 13].

In agent-based modelling, a system is modelled as a collection of independent decision-making entities, called *agents* [8]. An agent-based model essentially consists of a system of agents and the relationships between these agents. In this modelling method, each individual agent assesses its situation and executes various decisions or actions based on a set of established rules [8, 13]. These rules or parameters define the agent's behaviour, as well as different states in which the agent may reside. The transition between these states may be triggered by timers, received messages, conditions, rates, or agent arrival at any specified position in the model environment [8, 13].

Borshchev [13] suggests that agent-based modelling is more appropriate when the simulation developer possesses insight into how the objects in the system behave individually, rather than knowing how the system functions as a whole. An agent-based model is, therefore, typically constructed by following a bottom-up modelling approach, starting by first identifying the relevant objects or agents and then defining their behaviours. This modelling approach differs from the systems dynamics approach, which develops a model by following a top-down modelling approach [13].

4.3 Evaluation of simulation modelling approaches

When considering which simulation modelling approach is most appropriate for modelling the dynamics of diabetic health care in South Africa, the decision should be primarily based on the type of system being modelled and the purpose of this system [8, 13, 107]. Borshchev [13], however, also notes that the selection of a modelling approach is often largely influenced by the skill set or background of the simulation developer. Another significant consideration when selecting the modelling approach is what level of abstraction is most appropriate to model the system

In order to select the most appropriate modelling approach, discrete-event modelling, system dynamics modelling, and agent-based modelling are each evaluated based on the ability of the approach to meet the requirement specifications developed in §4.1. Since Borshchev [13] argues that the selection of a modelling approach is often largely influenced by the skill set or background of the simulation developer, 'ease of creation' is added as an additional requirement specification. A summarised description of the three modelling approaches and their capability to meet the requirement specifications according to the work of Banks [8], Borschev [13], Smith [101], Sterman [107], and Varga [121] is shown in Table 4.1.

TABLE 4.1: *Summary and evaluation of the simulation modelling approaches.*

Requirement specification	**Modelling approaches**		
	System dynamics	**Discrete-event**	**Agent-based**
Problem identification	Excellent	Very poor	Poor
Non-linear and dynamic intereactions	Very good	Very good	Excellent
Flexibility	Very good	Very good	Very good
Outcome accuracy	Excellent	Poor	Good
Indication of effect over time	Very good	Very good	Very good
Ease of creation	Good	Poor	Very poor

Discrete-event modelling is likely an inadequate approach for the intended modelling task, since the intervention strategies for a diabetic health care system should be viewed as a continuous flow of resources and information, rather than as discrete events in a process flow. Furthermore, the discrete-event approach typically focuses on the details of a system rather than from an holistic systems perspective [13, 121], and may, therefore, be unable to identify the effects of the various intervention strategies on the modelled system. This may not be ideal in the context of national health care and the diabetic population in South Africa, as both of these systems are almost always viewed from a high-level perspective. The 'Problem identification' and 'Outcome accuracy' requirement specifications are, therefore, indicated as 'Very poor' and 'Poor' in Table 4.1, as the discrete-event approach is not able unable to identify the effects of the various intervention strategies on the system modelled from an holistic perspective, and, consequently, may produce inaccuracies. An additional shortfall of the discrete-event approach is that the 'Ease of model creation' is deemed as poor [13, 121].

System dynamics modelling and agent-based modelling are, therefore, considered as the most appropriate modelling techniques to understand the effects of various intervention strategies to manage diabetes given the requirement specifications, as summarised in Table 4.1. Agent-based modelling is, however, rejected for the purposes of this research, as this approach is better suited for modelling a system at a low level of abstraction and from a bottom-up approach [8, 13]. In the case of agent-based modelling, the 'Problem identification' aspect is, therefore, scored 'Poor'. Although agent-based modelling is excellent at incorporating non-linearity in a system, it is also significantly criticised for its poor 'Ease of creation' [13].

Since the South African health care system, consisting of a multitude of stakeholders, as well as the diabetic population in South Africa, is to be investigated and modelled, the effects of diabetic policy interventions would be more effectively modelled a system dynamics perspective [13, 107], thereby scoring 'Excellent' for the 'Problem identification' requirement specification, and 'Very good' for the 'Non-linear and dynamic interactions' requirement specification. Furthermore, the system dynamics approach adapts well to varied input data and changes to interrelations, and also has the capabilities to provide the expected outcome of the system over a specified time period in order to model future predictions [107].

System dynamics has been shown to be an appropriate method for investigating a number of applications in the health sector [77] and in supporting public health policy [69]. It has also specifically been utilised in a study by Jones [50] to understand diabetics population dynamics in the USA. In 2003, the Center for Disease Control in the USA commissioned a dynamic model of diabetes prevalence and complications to design and evaluate intervention strategies in order to explore the potential of system dynamics for addressing chronic disease policy [42]. Another application of system dynamics was in a study by Rees *et al.* at Synergia Limited, who developed a system dynamics model to assist the development of strategic diabetes policy for Manukau, New Zealand [90].

System dynamics modelling is, therefore, selected as the appropriate approach to model the dynamics of diabetic health care in South Africa with the purpose of investigating existing intervention strategies for the management of diabetes.

4.4 The system dynamics method

As introduced in §4.2.1, the system dynamics method aims to analyse complex systems and problems. Jay Forrester created system dynamics as a method for analysing complex systems to aid and improve decision-making and policy formation [107]. This method was also developed to account for the behaviour in cause-effect relationships, delays and feedback loops in complex systems [68, 107].

As previously discussed, the system dynamics method is used to develop models that are simplifications of reality based on the understanding of the system and assumptions made regarding expected behaviour. While system dynamics modelling proves to be an extremely useful tool to assess the ability of a system to adjust to change and test alternative intervention strategies [68, 107], system dynamics modelling does, however, not guarantee accurate prediction of future system behaviour [13, 107]. System dynamics is rather more equipped to increase the understanding of behaviour and identifying expected trends related to changes in the system [107]. This specific characteristic of system dynamics adds to the appropriateness of the methods to investigate existing intervention strategies for the management of diabetes in South Africa.

This section begins by discussing the background of system dynamics, as well as the different stages and steps of the method. The modelling processes specific to the system dynamics method are subsequently discussed and system dynamics tools are introduced. The mathematical representations of stocks and flows are then shown, and the most applicable system dynamics validation and verification strategies are presented.

4.4.1 The modelling process

The system dynamics modelling approach follows a distinct modelling process for addressing any arising problem [13, 68, 107]. This section provides insight into this methodology by describing the different stages and steps used in system dynamics.

Background on the modelling process

Rubinstein and Firstenberg [95] were the first to define a process for the development of a model. To achieve a simple model with a high level of abstraction, Rubinstein and Firstenberg suggested five fundamental steps which should be followed:

1. Establish the purpose and objective of the model;
2. List the possible elements, observations, measurements and ideas that may relate to the purpose established in Step1;
3. Select the elements listed in Step 2 which are relevant to the purpose defined in Step 1;
4. Aggregate the identified elements into groups of similar classification; and
5. Repeat Step 4 several times until a model consisting of several elements, aggregated into approximately two groupings, emerge.

The generic process of Rubinstein and Firstenberg [95] is also utilised when developing a system dynamics model, as model development is typically an iterative process [13, 68, 107]. Since the system dynamics modelling process is a continuous process of formulating hypotheses, as well as testing and evaluating formal and mental models, many researchers have attempted to organise the modelling activities and processes (varying from five to eight different stages), each proposing a different set of arguments [34]. A summary of the most prominent system dynamics modelling processes are shown in Table 4.2. Despite the alternative grouping of activities in the system dynamics process, researchers commonly agree on the activities employed in the system dynamics method [13, 68, 107].

Modelling steps followed in this research

Although alternative system dynamics processes are presented in Table 4.2, the same system dynamics principles are utilised in each approach. In this research, Sterman's system dynamics

TABLE 4.2: *Summary of alternative system dynamics modelling processes.*

Meadows and Behrens [75]	Roberts [93]	Sterman [107]
General description of the problem observed	Problem definition	Problem articulation
Precise specification of models purpose		
Definition of time horizon		
Identification of major elements to be included	System conceptualisation	Dynamic hypothesis
Postulation of model structure	Model representation	Formulation
Estimation of parameters		
Evaluation of model sensitivity	Model behaviour	Testing
	Model evaluation	
Experimentation and simulation	Policy analysis and model use	Policy formulation and evaluation

modelling process is selected since it is the most widely used in the literature [68]. Sterman's process, which is thoroughly presented in his book entitled *Business Dynamics* [107], is very much an iterative one, as illustrated in Figure 4.1.

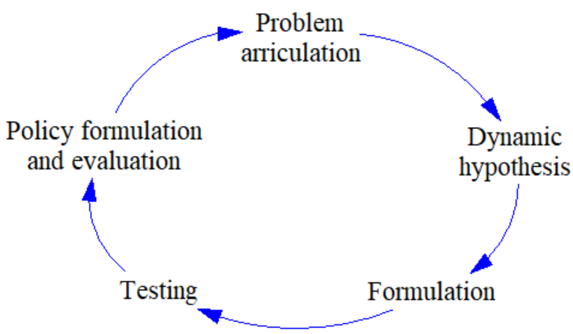


FIGURE 4.1: *Sterman's process for system dynamics modelling [107].*

The first step of the system dynamics modelling process is the *problem articulation* stage [107]. To ensure a successful modelling investigation, a clear purpose for the model must be established [68, 107]. The specific problem should, therefore, be clearly and comprehensively defined to ensure that the developed model is deemed useful for the situation under consideration. A useful model is one which simplifies reality, thereby easing the comprehension and understanding of the modelling steps to follow [68, 107]. A clear purpose is useful when clarifying the elements that should be included and excluded in the model. Finally, the scope and boundaries of the research are established, and preliminary information and data are collected [107].

Following the articulation of the problem, a conceptual model is formulated in the form of a *dynamic hypothesis* using a CLD [68, 107]. The dynamic hypothesis is, in essence, a theory of how the system developed its currently observed behaviour [68, 107]. This hypothesis is dynamic since it must be able to provide an explanation of the dynamics characterising the system, which are as a result of the underlying feedback, and the stock and flow network [107]. A thorough literature study is necessary to analyse the existing body of knowledge, and to identify the key variables and concepts to be considered for inclusion in a system CLD [34]. The structure and important elements of the diabetic health care system in South Africa was researched and documented in Chapters 2, 3 and 4.

In the *formulation* step, the CLD diagram developed in the previous step is acts as a basis for building the system dynamics simulation model using appropriate simulation software [107]. Although it is possible to transition into this phase directly after problem articulation, conducting the CLD step enhances the conceptional rigour and learning power of the system approach [34].

The completeness and wider insights of systems thinking are generally absent from other simulation modelling approaches, since causal loop modelling does not form part of their methodology [68, 107]. The simulation model is developed using CLDs, and corresponding stock and flow diagrams, and is constructed within an appropriate system dynamics modelling software. In this step, the variable types are defined and values for parameters, behavioural relationships, decision rules, and initial conditions are estimated or specified based on research — this largely depends on the type of variable or availability of information [68, 107]. The simulation model is then run over a specified time span in order to produce a model output, based on the current specified variables and conditions.

While *testing* is the fourth step of Sterman's system dynamics modelling process, verification and validation of the system dynamics model occurs during and after a simulation model's development [107]. Although some form of model validation and verification should occur at every step of the modelling process, a significant portion of formal verification and validation occurs after the initial model formulation and before the policy analysis design stage [107]. Testing the model does not only comprise of a simple replication of historical data, but is rather vital for identifying flaws in the construction of the model [68, 107]. Various rests are conducted on the simulation model to ensure dimensional consistency, gauge the sensitivity of model parameters and initial values, and highlight model assumptions [34]. The model must also be tested for extreme conditions that may not occur in the real world. Model equations, parameters and boundaries need to be verified so as to validate the model's behaviour over time [107].

In the fifth stage, known as the *policy formulation and evaluation* stage, various policies and strategies are formulated and tested after a reasonable measure of confidence is developed in both the model's structure and behaviour [68, 107]. Here the term 'policy' refers to changes to a single internal system's variable [107]. *Strategy* is a combination of a policies and, therefore, considers internal and controllable system changes [107]. When these strategies are tested under varying external conditions, *scenario modelling* occurs. It is imperative that the key drivers of change, factors and uncertainties which have a significant impact on the decisions, policies, and strategies evaluated are identified [34]. Scenarios may be defined by a plethora of environment conditions which may arise through specific changes to the system. Scenarios may also be developed by considering policy design, and which new decision rules, strategies, and structures may benefit from being testing in the modelling environment [107].

During all scenarios run, the performance of the policies and strategies outputted by the model is then analysed and evaluated [107]. The most effective scenarios are then presented as possible policy considerations [68, 107].

4.4.2 System dynamics tools

This section describes two specialised system dynamics tools needed to develop a system dynamics model. This section describes and discuss the concepts of CLDs and stock and flow diagrams, as introduced in §4.4.1.

Causal loop diagrams

In order to better understand the structure and behaviour of an identified problem, CLDs may be developed [13, 68, 107]. These aid the process of identifying key actors in the system and how these entities interact and influence each other. These CLDs provide the foundation for the stock and flow diagrams, where role-players are then identified as being either a *stock*, *flow*, *auxiliary*, or *exogenous* variable [107]. CLDs are especially beneficial to capture hypotheses about causes of the problem dynamics, eliciting and capturing mental models of individuals or teams, and communicating important feedbacks believed to be responsible for the behaviour of the system.

CLDs consist of variables connected by arrows which denote causal influences among the variables. The notations used in these diagrams are explained using Figure 4.2. This figure illustrates a simple CLD which shows the systems structure and behaviour of any given population [68, 107]. There are five variables in this CLD: Births, fractional birth rate, population, deaths, and average life span. Casual links are the lines with arrowheads that connect variables in a causal diagram.

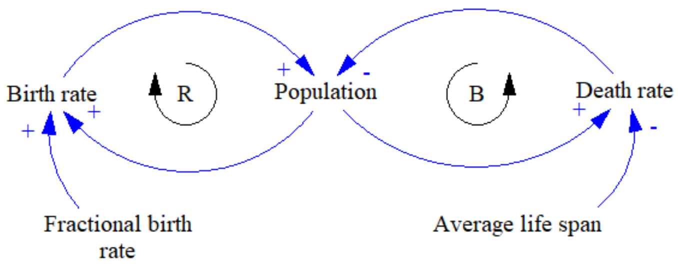


FIGURE 4.2: *Basic population CLD [107].*

If births occur, the size of the population will increase at a rate of the variable `fractional birth rate`. `Births`, therefore, have a positive (+) influence on *population*, as births add to population size. The larger the population, the higher the birth rate, as there are more individuals who can reproduce, which will, in turn, bring about more births (+). This notion is similarly applied to the relationship between population and deaths: If deaths are present, the population size will decrease at a rate of `average life span` and the influence on population is negative (−). Reinforcing loops (R) are positive feedback systems, which indicates that the feedback loop continues in the same direction [68, 107]. This results in either systematic growth or decline. Balancing loops (B) are the opposite of reinforcing loops, and are negative feedback systems [68, 107]. This indicates that the feedback loop alters direction, which results in a fluctuation in the system or a move toward equilibrium. Time delays may also be introduced in CLDs. Figure 4.3 depicts the causal relationship between a hospital's construction and the patient capacity of the hospital, where a time delay is indicated by the two horizontal lines.

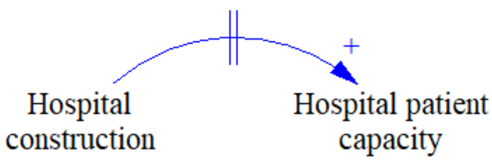


FIGURE 4.3: *Causal indicator with a delay marking.*

CLDs do, however, present a number of limitations — the most prominent being is its failure to capture what is actually happening in the system, but rather only what would happen should a change occur [68, 107]. It is therefore, imperative when employing the system dynamics method to use the CLD tool in conjunction with the stock and flow diagram.

Stocks and flow diagram

The essential features of a system dynamics model is the way in which the system being analysed is described in terms of stocks, flows (or rates), auxiliary variables and the feedback loops formed by these elements [68, 107]. The way in which these elements represent a system is critical to modelling the dynamics of the system. A summary and description of the elements used to construct a stock and flow diagram is provided in Table 4.3 [68, 107]. Using the stock and flow diagram elements shown in Table 4.3, the stock and flow diagram for the population causal loop depicted in Figure 4.2 can be constructed as shown in Figure 4.4.

TABLE 4.3: *Summary of elements used in a stock and flow diagram [68, 107].*

Element	**Element description**	**Element symbol**
Stocks	A stock represents entities in the system, where contents and levels of the stocks may fluctuate during the period of simulation. The level of the stock is cumulative of behaviour in previous time intervals.	Stock
Flows	Flows represent the movement of entities or units in the system between stocks or when entering or leaving the system. Equations governing flow provides the rate of the flows. In addition, flows can be physical or abstract.	
Valves	Valves represent the control flows and the rate at which entities or units move between stocks or when entering or leaving the system.	
Sources and sinks	A source represents an origin point from which flow may arise outside the boundary of the model. Sinks represent the exit point for flows to leave the model boundary.	
Auxillary variables	Auxillary variables represent variables influencing behaviour of stocks and flows.	Auxillary variable
Connectors	Connectors represent linkages between various elements in the system, which includes stocks, flows, auxilary variables, and valves.	

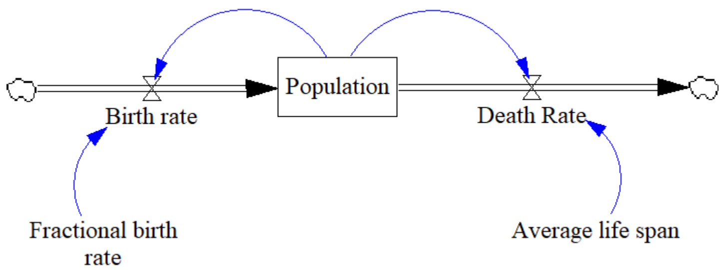


FIGURE 4.4: *Stock and flow diagram of a simple population model.*

Stocks and flow diagrams play a significant role in the development of a system dynamics model, as the state of the system is characterised using this diagram, as well as providing the basis for actions [68, 107]. Stock and flow diagrams also provide the system with inertia and memory, since the contents of a stock can only change with an associated inflow or outflow [68, 107]. In addition, a significant advantage the stock and flow diagram representation is the clear distinction between physical flows through the stocks and flows, and the information feedback loops which close the loops in the system [107].

4.4.3 Mathematical representations of stocks and flows

According to Sterman [107], the stock and flow diagram convention is largely based on the concept of the flow of water in and out of reservoirs. The number of units or quantity of material in any stock is the accumulation of material entering the stock minus the flow of material leaving the stock. Since stocks may accumulate or integrate their flows, the net flow into the stock is, therefore, the rate of change of the stock [107], and may be mathematically described as

$$Stock(t) = \int_{t_0}^{t} Inflow(s) - Outflow(s)ds + Stock(t_0). \tag{4.1}$$

The value of the inflow at a stock at some time s between the initial time t_0 and the current time t may be represented as $t\ Inflow(s)$ [107]. Similarly, $Outflow(s)$ represents the value of the outflow at a stock at some time s between the initial time t_0 and the current time t [107]. The net rate of change of any stock (or derivative) is the difference between the stock inflow and outflow, or

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t).$$

As a way of notion, the INTEGRAL() function is employed when referring to the accumulation of a stock, where the inflows and outflows are described as functions of the stocks [107], as well as of other state variables and parameters, which simplifies Equation (4.1) to

$$Stock = Integral(Inflow - Outflow) + Stock\ value\ at\ t_0.$$

4.4.4 System dynamics verification and validation

Model validation and verification is an important step in the system dynamics modelling process and should, therefore, be performed before investigating the behaviour of the model or performing policy analysis [89]. Model verification is the process of ensuring that the simulation model has been developed or simulated correctly, whereas model validation is the process of determining whether or not a model meets the aims and objectives of the initial research question [9, 89].

During the process of modelling, modellers typically partially verify and validate their model, but the act of *completely* validating and verifying a model simply not possible [9]. No model can ever be *fully* verified or validated, as all models, whether mental or formal, are limited, simplified representations of the real world [9, 10]. Despite the impossible task of validation, it is the responsibility of the modeller ensure that the best model is developed with the information they have at their disposal. Pruyt [89] describes an iterative method to verify a system dynamics model which includes checking and testing for (i) dimensional consistency, (ii) the appropriateness of the integration type and time size, and (iii) errors within the model equations and inputs.

In addition to Pruyt's method for system dynamics model verification, Lai and Wahba [60] developed a "Model Correctness Checklist" which may be employed to verify the build of the model and includes the following steps: (i) Units check, (ii) naming variables, (iii) no constants embedded in equations, (iv) mention parameter values in the documentation, (v) choose appropriately small time steps, (vi) stock values can be changed only by flows, (vii) every flow should be connected to a stock, (viii) flows should not be linked to auxiliary variables or to other flows, (ix) stocks should not be linked to stocks, (x) the use of IF THEN ELSE, MIN/MAX and other logic statements, (xi) use of initial values, and (xii) curving connectors.

System dynamics has typically been criticised for its lack of formal and quantitative validation and evaluation tools [9, 107]. More specifically, system dynamics has repeatedly been criticised for often relying too much on subjective, informal, and qualitative validation tests [9]. System dynamics models do, however, possess certain characteristics that deem standard statistical tests inappropriate [107]. Barlas [9] argues that the inappropriateness of statistical tests for system dynamics should not lead to the adoption of entirely qualitative validation procedures, but rather, to develop quantitative tests that are appropriate for the validation and evaluation of system dynamics models. Such tests, suggested by Barlas [9], would rather focus on major time patterns than rather individual data points.

The issue of validating causal-descriptive models (like system dynamics) is due to its connection with philosophy of science challenges [9]. The validity of a system dynamics model can be discredited if an analysis is able to show that a relationship in the model conflicts with an established relationship in the real world, even despite the case of the output behaviour of the model matching the observed system behaviour [9, 107]. For causal-descriptive models, the act of validating the model primarily involves validating the internal structure of the mode and not its output behaviour [9]. The model should essentially produce the 'right' behaviour for the 'right' reason.

The overall objective of the process of validating a system dynamics model is, therefore, to establish confidence in the usability of the model [9, 107]. While it is also important to validate and evaluate the accuracy and ability of the model to reproduce real-world behaviour, this validation is only valuable if sufficient confidence has been established in the structure of the model [9]. The logical order of system dynamics model validation is to first validate the structure of the model and only then to start testing the validity of the behaviour accuracy [9, 10]. This system dynamics validation procedure, proposed by Barlas [9], is shown in Figure 4.5. It can also be observed that, in Figure 4.5, all three stages of validation depend on the purpose of the model determined in the problem articulation step of system dynamics modelling process. No test of validity should, therefore, be conducted without reference to the specific purpose of the model.

In addition, tests for building confidence in system dynamics models, and for the purpose of validation, were further developed by Senge and Forrester [99] which are based on the direct structure, structure-orientated, and behaviour pattern tests, as proposed by Barlas [9, 10].

Direct structure tests

As may be seen in Figure 4.5, two types of structure tests exist: *Direct structure* tests and *Structure-oriented behaviour* tests [9]. Direct structure tests determine the validity of the model structure through the direct comparison of the model from knowledge on the real world system structure [9]. This involves taking each relationship individually, whether a mathematical equation or any form of logical relationship, and comparing it with available knowledge about the real world system. Forrester and Senge [99] give examples of direct structure tests which include structure and parameter confirmation tests, a direct extreme-conditions test, and a dimensional consistency test. The direct structure tests may also be empirical or theoretical [9]. Empirical structure tests involve the comparison of the model structure with either quantitative or qualitative information obtained directly from the real-world system being modelled, whereas

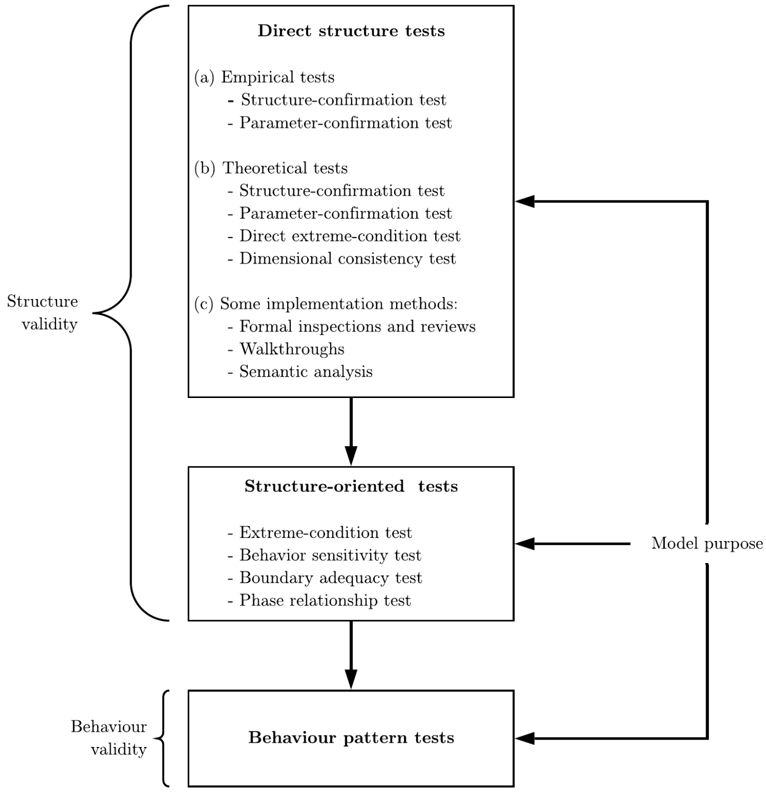


FIGURE 4.5: *Formal system dynamics model validation procedure [9].*

theoretical structure tests involve comparing the structure of the model with generalised knowledge about the system found in literature.

The empirical *structure confirmation* test is used to assess whether the purpose of the model is consistent with the real system [9, 99]. The objective of this validation test is to identify inconsistencies and inappropriate assumptions in the model. The structure assessment test is conducted on the model through the use of policy structure diagrams, causal diagrams, stock flow diagrams, and by inspection of the model [9]. Further input may be acquired through interviews and workshops to solicit expert opinions, archival materials, and review of literature [9, 10]. Furthermore, partial model test may be conducted on the intended rationality of the decision rules. Finally, suspect structures may be disaggregate before repeating sensitivity and policy analysis to assess the structure of the model. The second direct structure test, *parameter confirmation*, evaluates the constant model parameters against the knowledge of the real-world system [9, 10]. Conceptual confirmation of model validity is determined by identifying elements in the real world system that correspond to model parameters [9]. The parameter confirmation test may be applied both as an empirical test and as a theoretical test [9], as may be seen in Figure 4.5.

Another important direct structure test, called *direct extreme-condition* testing, involves testing the model for validity under extreme conditions by assessing the plausibility of the resulting values against the knowledge of what would typically happen under a similar condition in real life [9]. The model should behave realistically for any extreme input or policy in order to pass this validation step [9]. In the case of any implausible behaviour caused by extreme conditions, the model must be examined in detail to identify the precise source of the error [9, 10]. The extreme conditions test is conducted on the model by testing the model response to extreme values for each input, both alone and in combination with other inputs, as well as subjecting the model to large shocks in extreme conditions. Finally, the *dimensional consistency* test entails reviewing the right-hand side and left-hand side of each equation for dimensional consistency, which is typically one of the first validation tests to be conducted on the model [9]. The specification of units of measure should thus occur during the model development, opposed to after the model's development. This test is conducted to ensure that all variables and equations in the model are dimensionally accurate. The dimensional consistency test is conducted on the model through a dimensional analysis (which is a typical feature available in system dynamics software) and the inspection of model equations for inconsistent parameters [9].

Structure-oriented behaviour tests

The second general category of structural tests, called *structure-oriented behaviour* tests, assess the validity of the model structure indirectly through the application of certain behaviour tests on model-generated behaviour patterns, and generally involve simulation [9]. These structure-oriented tests may assist the modeller in uncovering potential structural flaws present in the model. Several of these tests are shown in Figure 4.5 and include: The extreme-condition test, behaviour sensitivity test, boundary adequacy test, and phase relationship test.

The indirect *extreme-condition* test involves the assignment of extreme values to selected parameters and then comparing the model-generated behaviour to the observed (or anticipated) behaviour of the real-world system under the same extreme conditions [9]. The *boundary adequacy* test determines whether the model boundary is appropriate for the specific model purpose [9, 10]. To determine the adequacy of the model boundary, the boundary adequacy test is conducted on the model through model boundary charts, sub-system diagrams, stock and flow diagrams, together with inspecting model equations [9]. Further tests include modifying the model to include plausible additional structure, such as making all constant and exogenous variables endogenous before repeating sensitivity and policy analysis. Finally the adequacy of the boundary may also be tested through the use of interviews and workshops to solicit expert opinion, review of literature, archival materials, and inspection of the system processes [9, 10].

The next structure-oriented behaviour test, called *behaviour sensitivity*, consists of determining the parameters to which the model is highly sensitive, and investigating whether the real-world system would present similar high sensitivity to the corresponding parameters [9]. Finally, the *phase-relationship* test establishes the phase relationships between pairs of variables in the model, which are obtained from the simulation [9]. If certain model phase relationships contradict the phase relationships which are observed in the real-world system, there exists a structural flaw in the model.

Behaviour pattern tests

The two categories of tests discussed in the two preceding sections were designed to test for the validity of the model structure. When sufficient confidence has been established in the validity of the model structure, tests designed to measure how accurately the model may reproduce the major behaviour patterns exhibited by the real world system may then be performed [9]. Here, significant focus is placed on pattern prediction, such as periods, trends, frequencies, phase lags, and amplitudes, rather than explicit point prediction [9, 10].

In the process of testing for behaviour validity, there are two fundamentally different types of behaviour patterns, which require two different types of behavioural tests. If the model involves a transient, non-stationary behaviour, such as that of an S-shaped growth, then a standard statistical measure would not be suitable when applied to the model [9]. Since the problem is not of statistical nature, no general statistical tests may be offered to test for the validity in this case. The best approach is rather to compare graphical and visual measurements of typical model behaviour-pattern characteristics, such as the amplitude of a peak, minimum value, maximum value, time between two peaks, slope, time to settle, or number of inflection points, to the expected measurements of the real-world system [9].

If the model system, however, involves a long-term steady-state simulation, then it is possible to apply specific standard statistical measures and tests to the model [9]. Barlas [9] developed a multi-step behaviour validation procedure for this specific case instance. Barlas' procedure first considered a trend comparison and removal, followed by a period comparison using the autocorrelation function [9]. The averages and variations are then compared to their respective values in two steps. The phase lag is then tested using the cross-correlation function. Finally, a discrepancy coefficient is determined [9].

If a model fails the behaviour pattern tests for either the transient or long-term steady-state, model revision must be made. In this case, however, since confidence in the model structure should already been established, model revisions would only involve parameter input changes, rather than structural revisions [9].

4.5 Chapter 4 conclusion

At the onset of Chapter 4, a set of requirement specifications were developed, in fulfilment of Research Objective II, to determine an appropriate method to investigate existing intervention strategies for the management of diabetes in South Africa. Thereafter, modelling approaches of a general nature were discussed and presented, which was followed by a description of the most notable modelling approaches, namely system dynamics, discrete-event and agent-based. The set of requirement specifications were then used to evaluate the aforementioned modelling approaches. From the evaluation, system dynamics was identified as the most appropriate approach to model the dynamics of diabetic health care in South Africa with the purpose of investigating existing intervention strategies for the management of diabetic health care, in fulfilment of Research Objective III. Finally, the system dynamics modelling approach was described in detail. The system dynamics modelling approach, identified and described in this chapter, is used to develop a model of the South African diabetic health care system in Chapter 5 so as to investigate alternative intervention strategies for the management of South African diabetic health care.

Part II

Investigation of intervention strategies for the management of diabetes in South Africa

CHAPTER 5

System dynamics modelling approach

Contents

The aim of Part II of this research is to use the system dynamics modelling approach to develop a system dynamics model to investigate the effects of existing intervention strategies on the management of diabetes in South Africa.

Chapter 5 begins by articulating the problem of the diabetic health care system in South Africa, as explored in Chapter 2. A dynamic hypothesis of the articulated problem is then presented in the form of a *Causal Loop Diagram* (CLD). The CLD is subsequently used to design and develop a stock and flow model of the diabetic health care in South Africa, in fulfilment of Research Objective IV, using an appropriate system dynamics software. Finally, the system dynamics model is verified and validated so as to establish the validity of the model, as well as to deem the model outputs to be accurate and credible, in fulfilment of Research Objective V.

5.1 Articulation of the problem

As mentioned in §4.4.1, the first phase of the system dynamics modelling approach in this research is the problem articulation or structuring. In order to determine the underlying problem of diabetic health care in South Africa, as well as to better understand and describe the system, and aid the articulation of the problem, a literature review was performed on the diabetes mellitus disease, diabetic policy and intervention strategies, with specific focus on South Africa, in Chapters 2 and 3, respectively.

The first section to follow builds on the literature reviewed in Chapter 2, with key points highlighted again, so as to develop the context of and provide insight into the problem for the purpose of model development. Thereafter, the model boundary is described, followed by introducing the preliminary information and data compiled for this study.

5.1.1 Problem context

Although diabetes was previously considered uncommon in South Africa, it is now being increasingly identified as a prevalent health problem due to demographic and lifestyle changes [71]. With more chronically-ill patients, public PHC facilities are under significant strain to dedicate sufficient resources to assist all patients. This in turn, minimises the available time allocated to other aspects of PHC, which includes intervention strategies such as screening and prevention through education [71]. In addition, the inequality between private and public health care, together with the increased burden of disease in South Africa, prove to be significant challenges that hinder the effective management of diabetes [71], as discussed in §2.2. Furthermore, the prevention and treatment of diabetes is a complex process, involving numerous role-players and stakeholders, such as government agencies, the health care system, communities and diabetic patients.

In order to facilitate the improved management of the diabetes disease with the aim of ultimately reducing diabetic complications, as well as reducing premature mortality from diabetes in South Africa, the South African DoH released the updated *Management of type 2 diabetes in adults at primary care level* policy to manage diabetes from a public health care sector perspective in 2014 [103], as mentioned in §2.3.3. The South African diabetic policy also coincides with the third goal of the United Nations' *Sustainable Development Goals* (SDGs) of ensuring healthy lives and promoting well-being for people of all ages [31]. The SDGs acknowledges that people worldwide are still suffering needlessly from preventable diseases and the excessive number of premature deaths should be addressed. In order to overcome diseases and ill health, the United Nations aims to focus, with concerted and sustained efforts, on population groups and regions which have been neglected [31]. This is in-line with the aforementioned objectives of the *Management of type 2 diabetes in adults at primary care level* policy.

Since the implementation of the *Management of type 2 diabetes in adults at primary care level* policy in 2014, the prevalence of type 2 diabetes has, however, steadily increased from 4.5% in 2010 to 7% in 2017 [47]. In addition, the proportion of all deaths in South Africa as a result of diabetes has increased from 5.1% in 2014 to 5.5% in 2017. As previously argued in §2.4, it is, therefore, necessary, to investigate existing policy and intervention strategies for the improved diabetic management in South Africa.

Drawing from the literature reviewed in Chapter 2, and building further on the hierarchical analysis of the management of the diabetic health care system in South Africa presented in §2.4.2, the following key areas or indicators for the management of diabetes in South Africa are identified within the problem context:

I Diabetic population;

II Prediabetic population;

III Diabetic complications;

IV Treatment procedure;

V Availability of medical equipment and pharmaceuticals, or resources;

VI Availability of health care professionals; and

VII Specific diabetic interventions.

In South Africa, the prevalence of diabetes has increased from 4% of the population in 2010 to 7% in 2018 constituting a *diabetic population* of 3.91 million South Africans based on current population estimates [47]. Of the estimated 3.91 million South Africans with diabetes, 61.1% are undiagnosed and are unaware of their heath condition [35]. The most significant factor is, however, that an estimated *prediabetic population* of 5 million South Africans exist [71]. Furthermore, the Centre for Disease Control and Prevention has reported that only 10% of prediabetics are diagnosed [42]. When the diabetes disease progresses, *diabetic complications* may arise, as mentioned in §2.1.6. Of all persons with diabetes in South Africa, 51.9% have developed diabetic complications either in the form of heart disease, loss of vision, kidney failure or amputation of the extremities [103]. Diabetic complications, such as vision loss, nerve damage and infections which may lead to amputations, only, however, increase the likelihood of injuries and accidents. Diabetic complications, such as heart disease and kidney disease have fatal consequences.

In the 2014 *Management of type 2 diabetes in adults at primary care level* policy, an extensive diabetic *treatment procedure* is outlined to management diabetes at its different disease stages, as described in §2.1.5. Since 61.1% of diabetics in South Africa are undiagnosed [71], these diabetics are not exposed to any form of treatment procedure. As a result, undiagnosed prediabetes, diabetes and diabetes with complications generally progresses to their respective following stage of diabetes at a quicker rate than diagnosed cases [103]. If the diabetic disgnosis treatment procedure is not performed routinely and effectively, this would result in prediabetes being more likely to progress to full-blownf diabetes, which, in turn, would increase the number of diabetic complications [103]. The effectiveness of the treatment procedure is largely influenced by the *availability of medical resources* required to provide diabetic care, as discussed in §2.1.5. According to the WHO [152], the medical resources and equipment necessary for the effective treatment procedure of diabetes is commonly unavailable, as previously seen in Table 3.2.

In addition to the required effectiveness, the diabetic treatment procedure needs to be performed routinely, according to the specifications stipulated in Tables 2.4, 2.5, and 2.6. The public health care system is, however, significantly overburdened, faced with the overwhelming task of serving 84% of the South African population [71] with only 30% of all South African physicians [54]. The relatively lower number of health care providers, along with the increased number of patients relying on public care, results in an overburdened public care system, when compared to that of the private sector. It is also argued that public health care workers are, in turn, overworked and thus find it challenging to provide the same level of personalised services as the private sector [54]. This was clearly observed in a study conducted at Tafelsig Clinic by Maillacheruvu [71], where clinicians were often overworked, and were unable to provide the health care required to serve all patient present at the clinic [71]. Consequently, it is evident that the *availability of health care professionals* is a limiting factor for performing routine diabetic check-ups, as required by the diabetic treatment procedure.

Finally, *specific diabetic interventions* play a significant role in the diagnosis and management of the various stages of diabetes. As described in §3.3.2, during the analysis of the intervention strategies of other prominent non-communicable diseases, decreases in the number of breast cancer and lung cancer deaths may be largely attributed to proactive intervention strategies, such as early detection though screening and preventative education, opposed to reactive policy. In addition, the process of educating diabetics to self-manage their desease (*i.e.* patient self-management) has proven to be a useful tool in the management of prediabetes and diabetes, and positively contributes towards preventing the onset of the diabetes disease with complications [41]. Regular screening, diabetic awareness, and self-management education may, therefore, be effective interventions for managing the diabetes disease.

5.1.2 Model boundary

As discussed in §1.5, several assumptions must be made in this research, one of which includes assumptions about the model boundary.

In order to assess the implications of existing intervention strategies to aid the management of diabetes in South Africa, the model assumes and simulates the South African public health care system as a self-contained system, and is thus not influenced by the South African private health care system. South Africa is also modelled as an isolated country. It is further assumed that South African legislative and other qualifying criteria, as stipulated in the *Management of type 2 diabetes in adults at primary care level*, are met. The model, therefore, only aims to indicate effects on the key areas previously identified in §5.1.1.

The goals and objectives of the *Management of type 2 diabetes in adults at primary care level* are in-line with that of the United Nations' SDGs — more specifically, goal three, which aims to ensure healthy lives and promote well-being. The time horizon for the system dynamics model may, therefore, be modelled in a similar way to the SDGs, which runs until 2030. As the *Management of type 2 diabetes in adults at primary care level* policy was released and implemented in 2014, it is considered appropriate to begin the modelling from 2014, so as to provide accurate data for model validation and improve model accuracy.

Although many variations of diabetes exist, only type 2 diabetes is investigated in this study. This is primarily due to the fact that type 2 diabetes afflicts 95% of those diagnosed with diabetes (as discussed in §2.1.2) and, therefore, warrens a greater importance for investigate this specific diabetes variation. The model population is also limited to the South African population over the age of eighteen, due to the relatively low prevalence of diabetes below this age and the lack of data available regarding the number of adolescent diabetics in the South Africa.

It is important to note that, although there exists a wide variety of diabetic complications, the majority of complications (such as vision loss, nerve damage, and amputations) only affect quality of life of a diabetic and are not fatal in nature. Diabetic complications like heart disease and kidney disease can, however, lead to death. Since this research focuses on the dynamics of the diabetic populations (as outlined in §1.5), only fatal diabetic complications are considered when modelling the dynamics of diabetics with complications.

5.1.3 Preliminary information and data

In order to establish the structure of the diabetic health care management in South Africa as a complex interrelated system, an investigation into the main drivers and policies present within the system is required. A literature review was, therefore, performed on the diabetes mellitus disease and diabetic policy and intervention strategies, with a specific focus on South Africa in Chapters 2 and 3, respectively.

Multiple studies exist which consider the use of system dynamics to model diabetic health care for policy formulation [14, 42, 50, 57] — these studies, however, focus on diabetic health care within the context of a *developed* nation. Two studies exist which employ system dynamics to investigate diabetic health care for policy formulation in South Africa. Thomas *et al.* [114] models the South African diabetic population and the progression towards diabetic complications, while presenting the non-diabetic population as an exogenous variable in order to determine the most effective reactive policy interventions to manage the disease. Thomas *et al.* [115] also goes on to investigate prediabetic health care in South Africa and the influence of proactive policy interventions in managing the prediabetic and diabetic populations. Both of the aforementioned studies investigate a specific component of diabetic health care in South Africa using system dynamics, and are used as a basis for providing insight for the remainder of this research.

All policy and legislative parameters are drawn from the *Management of type 2 diabetes in adults at primary care level* policy published by the South African DoH in 2014 [103]. Data relating to the diabetes populations and resource requirements in South Africa are gathered from the WHO diabetes profile on South Africa [152] (as discussed in §3.4.2), and from the IDF analysis of diabetes in South Africa [47].

5.2 Dynamic hypothesis of diabetic health care in South Africa

This section aims develop a dynamics hypothesis that theorises how the diabetic health care system operates based on its current observed behaviour. This hypothesis is dynamic, as it provides an explanation of the dynamics characterising the diabetic health care system in terms of the underlying feedback. At the onset of this section, the key variables of the diabetic health care system are identified. The dynamic hypothesis is then presented in the form of a CLD, and the feedback loops are described in detail.

5.2.1 Identification of main variables

During model conceptualisation, Forester [30] argues that CLDs should not be used as the starting point for model development, since it does not identify the level variables responsible for the dynamic behaviour observed in a system. It is, therefore, recommended that the system levels should be identified before the flow rates and causal effects of the system in a CLD [30]. During this conceptual model development phase, main variables and indicators are identified, together with the key leverage and intervention points.

As discussed in §2.4.2, it is useful to view the management of diabetic health care in South Africa from an hierarchical perspective in order to identify system levels according to macro-, meso-, and micro-perspectives. Building on the literature reviewed in Chapter 2, the hierarchical analysis of the management of the diabetic health care system in South Africa in §2.4.2, and the key areas for diabetic intervention identified in §5.1.1, the various elements observed within the South African diabetic health care system are categorised according to the appropriate system levels, as shown in Table 5.1.

Within the macro-level shown in Table 5.1, the South African DoH is identified as the primary element and actor. Since the South African DoH develops and releases the diabetic policy for the South African diabetic health care system, all diabetic interventions strategies and policy are, therefore, implemented from the perspective of the South African DoH. As discussed in §2.4.2, diabetic policy is considered to fall within the meso-level of the hierarchical perspective of South Africa's diabetic health care system. Six intervention points are identified as being part of the meso-level policy domain based on literature reviewed in Chapter 2, as may be seen in Table 5.1. As discussed in §2.4.2, the policy domain was identified as a key area for investigation in the management of diabetes in South Africa — the six aforementioned elements, therefore, serve as key areas for diabetic intervention during model conceptualisation. Finally, four elements are identified as being part of the micro-level of the hierarchical perspective, as shown in Table 5.1. These elements consist of the various diabetic populations and the health care professionals — all of which operate within the policy and intervention strategies guidelines outlined in the aforementioned meso-level.

TABLE 5.1: *The categorisation of the various elements observed within the South African diabetic health care system according to an hierarchical perspective.*

Hierarchical perspective	Elements	Description
Macro-level	South African Department of Health	The South African national body govering the health care within the country and the developer of national diabetic policies.
Meso-level	Treatment procedure	The procedure detailed within the national diabetic policy to manage and treat the diabetic disease from a public health care perspective.
	Health care professional to patient ratio	The number of health care professionals available to perform the diabetic treatment procedure and to conduct education interventions to patients in relation to the total prediabetic, diabetic and diabetic with complications populations in South Africa.
	Patient self-management intervention	Patient self-management education to encourage patients to self-manage their disease so as to promote recovery from a prediabetic state, as well as to prevent diabetic onset and progression to diabetic complications.
	Screening intervention	Screening of high-risk individuals to diagnose prediabetes, diabetes or diabetes with complications to improve the effectiveness of the treatment procedure.
	Education awareness intervention	Diabetic awareness education to the non-diabetic population to prevent prediabetic onset and to the prediabetic population to encourage prediabetic recovery, as well as to prevent diabetic onset from a prediabetic state.
	Available medical equipment and pharmaceuticals	The medical tools and pharmaceuticals needed to perform the diabetic treatment procedure.
Micro-level	Prediabetic population in South Africa	The total number of people in South Africa with a blood glucose level of between 6.1–6.9 mmol 1^{-1}.
	Diabetic population in South Africa	The total number of people in South Africa with a blood glucose level higher than 7.0 mmol 1^{-1}.
	Diabetics with complications population in South Africa	The total number of people in South Africa with a blood glucose level higher than 7.0 mmol 1^{-1} that have developed diabetic complications.
	Health care professionals	The number of health care professionals available to perform the diabetic treatment procedure and to conduct education interventions to patients.

5.2.2 Causal loop diagram

Using the main variables identified in §5.2.1, a dynamic hypothesis for the diabetic health care in South Africa is developed in the form of a CLD, and is illustrated in Figure 5.1. This CLD consists twelve feedback loops, which are defined as follows:

I *Influence of prediabetes on the availability medical equipment and pharmaceuticals* (R1);

II *Influence of diabetes on the availability medical equipment and pharmaceuticals* (R2);

III *Influence of diabetes with complications on the availability medical equipment and pharmaceuticals* (R3);

IV *Influence of prediabetic population on health care professional to patient ratio* (R4);

V *Influence of diabetic population on health care professional to patient ratio* (R5);

VI *Influence of diabetics with complications population on health care professional to patient ratio* (R6);

VII *Influence of patient self-management on the prediabetes population* (R7);

VIII *Influence of patient self-management on the diabetes population* (R8);

IX *Influence of patient self-management on the diabetes with complications population* (R9);

X *Influence of the implementation of interventions on the prediabetes population* (B1);

XI *Influence of the implementation of interventions on the diabetes population* (B2); and

XII *Influence of the implementation of interventions on the diabetes with complications population* (B3).

Each feedback loop of the CLD is described in the subsections to follow.

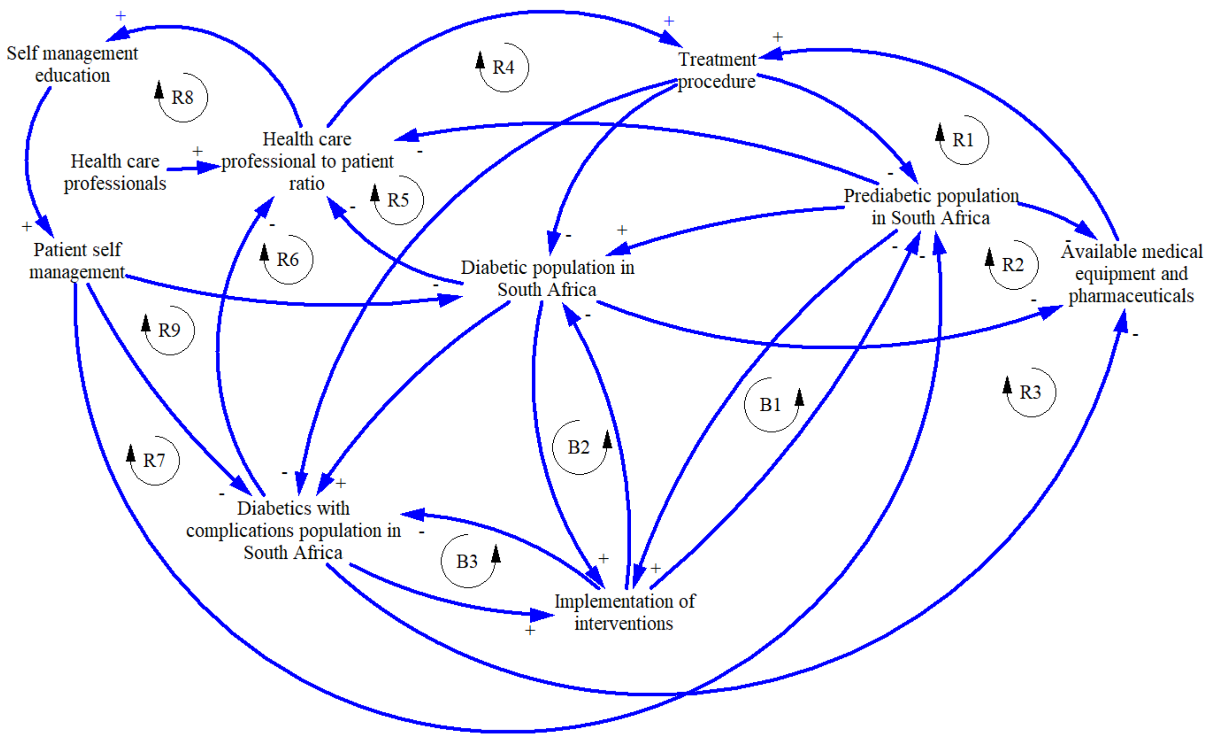


FIGURE 5.1: *Dynamic hypothesis of diabetic health care in South Africa.*

R1: Influence of prediabetes on the availability medical equipment and pharmaceuticals

The *influence of prediabetes on the availability medical equipment and pharmaceuticals* (R1) is a reinforcing loop in Figure 5.1. In this feedback loop, it may be observed that, as the prediabetic population in South Africa increases, the less the resources (*i.e.* medical equipment and pharmaceuticals) available in the public health care sector, since a fixed number of resources must be shared amongst more prediabetic patients. As discussed in §2.1.5, available and functioning equipment, as well as regular, sustainable supply of medication, syringes, and consumables are needed to follow the diabetic treatment procedures, as outlined in the South African diabetic policy *Management of type 2 diabetes in adults at primary care level*. When the availability of medical equipment and pharmaceuticals is limited, this results in a decreased adherence of the diabetic treatment procedures in all diabetics consultations, as medical equipment and pharmaceuticals are necessary to perform effective diabetic treatment procedures [103]. Consequently, a decreased adherence in the diabetic treatment procedures in consultations results in the disease being ineffectively treated and managed, which would may lead to an increased prediabetic population in South African. In addition, the treatment procedure plays a significant role in diagnosing the diabetes disease at its various stages, esspecially when checking for undiagnosed diabetes in high-risk patients [103]. When there is less adherence to the treatment procedure, the diagnosis of prediabetic patients decreases, which, consequently, increases diabetic population groups, as may be seen in Figure 5.1.

R2: Influence of diabetes on the availability of medical equipment and pharmaceuticals

The causal effects of the *influence of diabetes on the availability of medical equipment and pharmaceuticals* reinforcing loop R2 in Figure 5.1 are similar to feedback loop R1, where the influence of the prediabetics population on the availability of medical equipment and pharmaceuticals is shown. The difference between feedback loop R1 and R2 is that the decrease in the *available medical equipment and pharmaceuticals* is due to the increase in the *diabetic population in South Africa*, rather than an increase in the *prediabetic population in South Africa*.

R3: Influence of diabetes with complications on the availability of medical equipment and pharmaceuticals

The causal effects of the *influence of diabetes on the availability of medical equipment and pharmaceuticals* reinforcing loop R3 in Figure 5.1 are similar to feedback loop R1, where the influence of the prediabetic population on the availability of medical equipment and pharmaceuticals is shown. The difference between feedback loop R1 and R3 is that the decrease in the *available medical equipment and pharmaceuticals* is due to the increase in the *diabetic with complications population in South Africa*, rather than an increase in the *prediabetic population in South Africa*.

R4: Influence of prediabetic population on health care professional to patient ratio

The *influence of prediabetic population on health care professional to patient ratio* (R4) is a reinforcing loop in Figure 5.1. In this feedback loop, it may be observed that, as the prediabetic population in South Africa increases, the health care professional to patient ratio in the public health care sector decreases, since a fixed number of health care professionals must be shared amongst more prediabetic patients. As discussed in §2.1.5, a sufficient number of well-trained and dedicated health care professionals are required to administer the diabetic treatment procedures, as outlined in the South African diabetic policy *Management of type 2 diabetes in adults at primary care level*. When the health care professional to patient ratio decreases, this results in a decreased adherence of the diabetic treatment procedures in all diabetics consultations, as a sufficient number of health care professionals are necessary to perform effective diabetic treatment procedures, as previously described.

R5: Influence of diabetic population on health care professional to patient ratio

The causal effects of the *influence of diabetic population on the health care professional to patient ratio* reinforcing loop R5 in Figure 5.1 are similar to feedback loop R4, where the influence of the prediabetic population on the health care professional to patient ratio is shown. The difference between feedback loop R4 and R5 is that the decrease in the *health care professional to patient ratio* is due to the increase in the *diabetic population in South Africa*, rather than the increase in the *prediabetic population in South Africa*.

R6: Influence of diabetics with complications population on health care professional to patient ratio

The causal effects of the *influence of diabetics with complications population on the health care professional to patient ratio* reinforcing loop R6 in Figure 5.1 are similar to feedback loop R4, where the influence of the prediabetic population on the health care professional to patient ratio is shown. The difference between feedback loop R4 and R6 is that the decrease in the *health care professional to patient ratio* is due to the increase in the *diabetic with complications population in South Africa*, rather than the increase in the *prediabetic population in South Africa*.

R7: Influence of patient self-management on the prediabetes population

The *influence of patient self-management on the prediabetes population* (R7) is a reinforcing loop in Figure 5.1. In this feedback loop, it may be observed that, as the prediabetic population in South African increases, the health care professional to patient ratio in the public health care sector decreases, again since a fixed number of health care professionals must be shared amongst more prediabetic patients. When the health care professional to patient ratio decreases, the availability of the health care professional who are able to administer self-management education to a patient is less, due to the increased number of patients. As discussed in §5.1.1, diabetic self-management has shown to be a useful tool in the management of prediabetes and diabetes, and positively contributes towards preventing the onset of the diabetes disease and its progression to complications. If self-management education is decreased, a patient is less equipped to self-manage their disease. When a prediabetic patient does not self-manage or monitor their diabetes, prediabetic recovery is less likely, leading to a maintained or increased prediabetic population, as may be seen in Figure 5.1.

R8: Influence of patient self-management on the diabetes population

The causal effects of the *influence of patient self-management on the diabetes population* reinforcing loop R8 in Figure 5.1 are similar to feedback loop R7, where the influence of patient self-management on the prediabetes population is shown. The difference between feedback loop

R8 and R7 is that the increase in *patient self-management* leads to a decrease in the *diabetic population in South Africa*, rather than a decrease in the *prediabetic population in South Africa*.

R9: Influence of patient self-management on the diabetes with complications population

The causal effects of the *influence of patient self-management on the diabetes with complications population* reinforcing loop R9 in Figure 5.1 are similar to feedback loop R7, where the influence of patient self-management on the prediabetes population is shown. The difference between feedback loop R9 and R7 is that the increase in *patient self-management* leads to a decrease in the *diabetic with complications population in South Africa*, rather than a decrease in the *prediabetic population in South Africa*.

B1: Influence of the implementation of interventions on the prediabetes population

The *influence of the implementation of interventions on the prediabetes population* (B1) is a balancing loop in Figure 5.1. In this feedback loop, it may be observed that, as the prediabetic population in South Africa decreases, the South African DoH is less likely to implement diabetic policy interventions, such as screening for early detection or preventive education due to the decreased need for such interventions, since the prediabetic population in South African is decreasing. This action with a delay, however, leads to an increase in the prediabetic population in South African, since less patients are being screened, which prevents the diagnosis of the disease, as well as education to better manage and treat the disease. Consequently, the prediabetic population in South African increases in this case, as shown in Figure 5.1.

B2: Influence of the implementation of interventions on the diabetes population

The causal effects of the *influence of the implementation of interventions on the diabetes population* in balancing loop B2 in Figure 5.1 are similar to balancing loop B1, where the influence of the implementation of interventions on the prediabetes population is shown. The difference between balancing loop B2 and B1 is that the increase in the *implementation of interventions* variable leads to a decrease in the *diabetic population in South Africa*, rather than a decrease in the *prediabetic population in South Africa*.

B3: Influence of the implementation of interventions on the diabetes with complications population

The causal effects of the *influence of the implementation of interventions on the diabetes with complications population* in balancing loop B3 in Figure 5.1 are similarly to balancing loop B1, where the influence of the implementation of interventions on the prediabetes population is shown. The difference between balancing loop B3 and B1 is that an increase in *implementation of interventions* leads to a decrease in the *diabetics with complications population in South Africa*, rather than a decrease in the *prediabetic population in South Africa*.

5.3 Stock and flow model of diabetic health care in South Africa

Following the articulation of the problem in §5.1 and the formulation of a dynamic hypothesis in §5.2, a stock and flow model was developed in the *Vensim DSS* software so as to investigate the dynamics of the diabetic health care in South Africa, as well as for testing of possible existing intervention strategies for the management of diabetes South Africa. During the model development, subject-matter experts were consulted with regards to the diabetic health care system, as well as on the build and structure of the system dynamics model developed in this research.

At the onset of this section, an overview of the system dynamics stock and flow model is first presented. Thereafter, the aforementioned population stocks and flows of the model are described. The initial variables and parameters are then presented so as describe the initial conditions of the model, together with any variable assumptions. Thereafter, the assumptions for the non-linear relationships in the model are described. Finally, the decision points of the model and key areas for system intervention are identified and described.

5.3.1 Model structure overview

The developed stock and flow model demonstrates the dynamics of the non-diabetic, prediabetic, diabetic and diabetic with complications populations in South Africa, and enables the exploration of the twelve dynamic hypothesis developed in §5.2. Figure 5.2 displays the basic causal structure of the system dynamics model developed in the *Vensim DSS* software. The full structure also includes an inflow of population growth and outflows of non diabetes-related, prediabetic and diabetic deaths. This structure is grounded in the scientific literature on diabetes, policy, and related topics.

As is the case in all models, the model presented in Figure 5.2 is a simplification of the real-world system. Model parameters were calibrated based on historical data available for the South African adult population, as well as estimates from the scientific literature. All policy and legislative parameters are collected from the *Management of type 2 diabetes in adults at primary care level* policy published by the South African DoH in 2014 [103]. Data relating to the diabetes populations and resource requirements in South Africa are gathered from the WHO diabetes profile on South Africa [152], and from the IDF analysis of diabetes in South Africa [47]. These variables and parameters are now further discussed.

At the core of the model, shown in Figure 5.2, is a chain of population stocks and flows portraying the movement of people into and out of the following stages: (i) Non-diabetic, (ii) prediabetes, (iii) diabetes, and (iv) diabetes with complications. The prediabetes, diabetes, and diabetes with complications stages are further divided among stocks of people whose conditions are either diagnosed or undiagnosed. Diagnosis has dynamic significance, as it is necessary for proper management and control of hyperglycemia and may, in turn, greatly reduce the rates of diabetes onset, progression, and death [103].

Beyond the population stocks, Figure 5.2 indicates the potentially modifiable influences in the model that affect the rates of population flow, including influences which may be directly amenable to policy intervention. These modifiable influences include the following variables: `Detection of prediabetes`, `Detection of diabetes`, `Risk for diabetes and prediabetes`, `Management of prediabetes`, and `Management of diabetes`.

As shown in Figure 5.2, prediabetes and diabetes detection may be impacted by two interventions, namely: The glucose screening of high-risk individuals and through the treatment

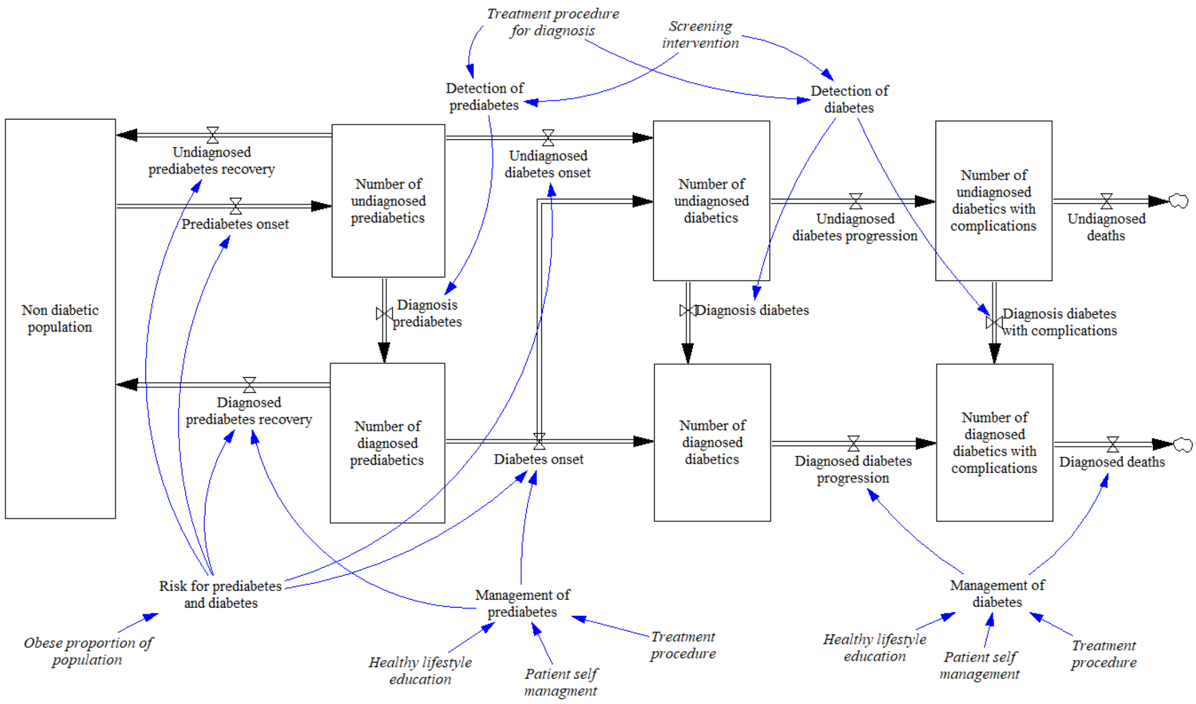


FIGURE 5.2: *An overview of the system dynamics model structure showing primary population stocks (boxes) and flows (arrows with valve symbols and cloud symbols for the progression to later clinical stages of diabetes), modifiable factors affecting flows (roman), and inputs amenable to policy intervention.*

procedure for diagnosis [50]. As may be seen in the CLD of Figure 5.1, the treatment procedure is influenced by health care professionals-to-patient ratios and the availability of medical equipment and pharmaceuticals. Since obesity is the leading modifiable risk factor for prediabetes and diabetes (for people with prediabetes) [41], the risk for prediabetes and diabetes is impacted by the obese proportion of the population. The management of prediabetes and diabetes may be impacted by three interventions, namely: Encouraging patients to self-monitor glucose levels through education by health care professionals, adopting healthy lifestyles through education, or by maintaining the treatment procedure [50], as prescribed by the DoH [103].

5.3.2 Population stocks and flows

As shown in §5.3.1, the developed stock and flow model comprises various stocks and flows so as to model the dynamics of the diabetes disease within South Africa. The objective of this sub-section is, therefore, to describe how each stock and flow is used to model the disease dynamics, as well as any assumptions made in the model.

At the onset of this sub-section, the population inflow and deaths are first described. Thereafter, the diagnosis of prediabetes, diabetes, and diabetes with complications is discussed, followed by the prediabetes onset and recovery, as well as the diabetes onset and progression.

Population inflow and deaths

The model's complete population structure is shown in Figure 5.3 and consists of seven stocks and eighteen flows. The population is represented and divided into one stock of the non-diabetic, two stocks of prediabetics, and four stocks of diabetics. Individuals are assumed to enter the population structure as non-diabetic at an inflow with a constant birth rate. All flows in the model, including the population inflow, are expressed in people per year. After entering the non-diabetic population, individuals may develop prediabetes (a reversible condition). From prediabetes, individuals may either recover to a non-diabetic state or develop diabetes (an irreversible condition) without disease complications. Diabetics without complications can, however, develop complications.

Cases of prediabetes or diabetes without complications are initially undiagnosed, but may become diagnosed by screening the high-risk population or by implementing diabetic treatment procedures. There may be cases in which the progression to complicated diabetes is still undiagnosed, but the arising symptoms would require specific medical attention, which would lead to the diagnosis of the disease. It may be observed that every population stock in Figure 5.3 has an outflow of death. In the case of the non-diabetic population, prediabetes, and diabetes without complications stocks, the deaths occur at age-normal rates or the average South African life expectancy, as the individuals are unaffected by diabetic complications. For the complicated diabetes stocks, however, the death flows are influenced by a diabetic complications-related life expectancy.

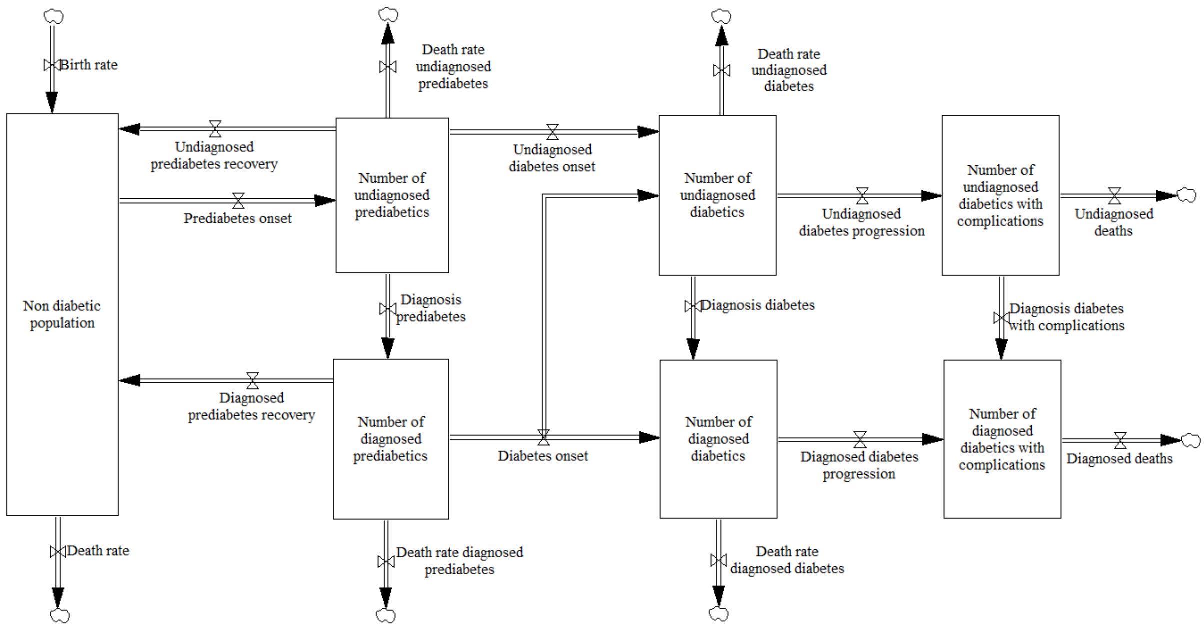


FIGURE 5.3: *Population stocks and flows.*

Diagnosis of prediabetes, diabetes and diabetes with complications

In this section, the following flows illustrated in Figure 5.3 are discussed:

I `Diagnosis prediabetes` flow;

II `Diagnosis diabetes` flow; and

III `Diagnosis diabetes with complications` flow.

As shown in Figure 5.2, the `Diagnosis prediabetes` flow is influenced by the `Detection of prediabetes` variable. The `Diagnosis prediabetes` flow is, therefore, defined to operate at a rate of *person per year* equal to

$$Number\ of\ undiagnosed\ prediabetics \times (Detection\ of\ prediabetes),$$

since the product of the rate of detection of prediabetes and the number of undiagnosed prediabetics results in the rate of diagnosed prediabetics per year.

The `Diagnosis diabetes` flow is, however, influenced by the `Detection of diabetes` variable. The `Diagnosis diabetes` flow is, therefore, defined to operate at a rate of *person per year* equal to

$$Number\ of\ undiagnosed\ diabetics \times (Detection\ of\ diabetes),$$

as the product of the rate of detection of diabetes and the number of undiagnosed diabetics results in the rate of diagnosed diabetics per year. The `Diagnosis diabetes with complications` flow follows the same logic.

From Figure 5.2, it may be seen that two modifiable factors influence the `Detection of prediabetes` and `Detection of diabetes` variables. As shown in Figure 5.1, both the screening intervention and the treatment procedure for diagnosis influence the three diabetic populations independently, therefore, resulting in an or-logic relationship. It may, therefore, be shown that both the `Detection of prediabetes` and `Detection of diabetes` variables operate at a rate of *dimentionless per year* equal to

$$1 - (1\ -\ Treatment\ procedure\ for\ diagnosis)\ \times\ (1\ -\ Screening\ intervention).$$

In order to demonstrate the workings of the `Detection of prediabetes` and `Detection of diabetes` variables, an extract of the complete system dynamics stock and flow model is shown in Figure 5.4.

When considering the `Treatment procedure for diagnosis` variable, it may be seen in Figure 5.4 that this variable is influenced by the availability of medical resources and the health care professional to patient ratio. This observation is in-line with the CLD in Figure 5.1, where both the available medical equipment and pharmaceuticals and health care professional to patient ratio influence the treatment procedure. Due to this observation in the CLD that both the influence of both the availability of medical resources and the health care professional to patient ratio influence the treatment procedure at the same instance, this results in an and-logic relationship.

It may be shown that the `Treatment procedure for diagnosis` variable operates at a rate of *dimentionless* equal to

$$\begin{aligned}&Effect\ of\ availability\ of\ medical\ resources\ on\ treatment\ procedure\ for\ diagnosis\\ \times &Effect\ of\ health\ care\ professional\ to\ patient\ ratio\ on\ treatment\ procedure\ for\\ &diagnosis.\end{aligned}$$

Furthermore, it can be seen in Figure 5.4 that both the availability of medical equipment and pharmaceuticals and the health care professional to patient ratio are ultimately influenced by

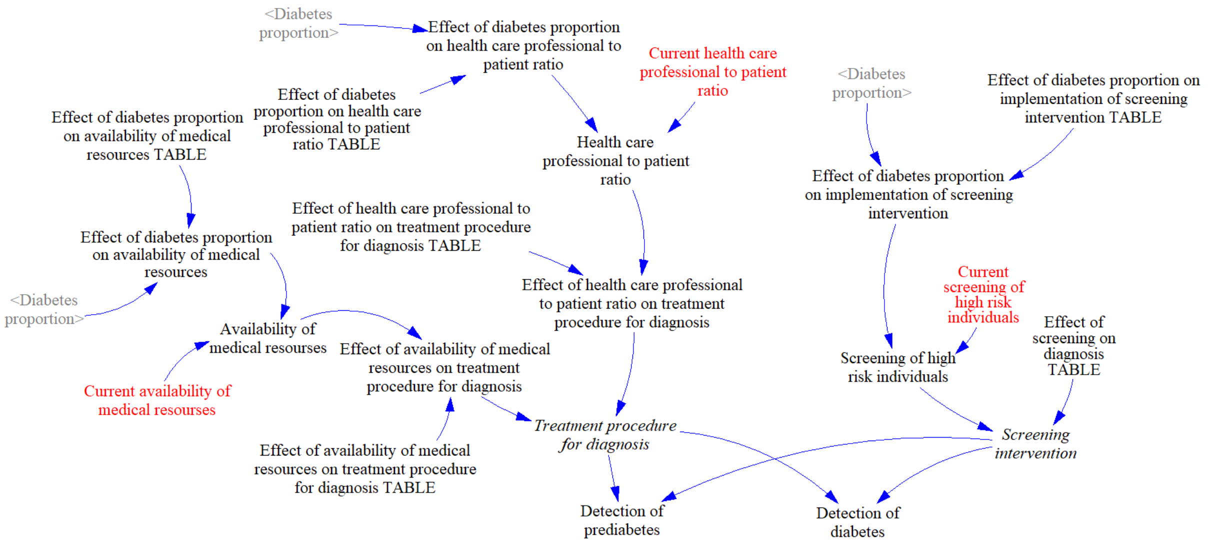


Figure 5.4: *Extract of the complete system dynamics stock and flow model demonstrating the detection of prediabetes and diabetes.*

the `Diabetes proportion` variable, which is the ratio of the diabetic population to the total population. This is again in-line with the CLD in Figure 5.1, where the diabetic populations influence both the availability of medical equipment and pharmaceuticals and the health care professional to patient ratio.

It should be noted that the system dynamics model currently uses the diabetic populations as a driver to influence the availability of medical equipment and pharmaceuticals. This may be similarly found for the health care professional to patient ratio, the implementation of screening interventions, and the implementation of education interventions. The use of the diabetic populations is to demonstrate the overburdened public health care system and the limit of medical resources available. The model may, however, benefit from a so-called `Health care system workload` variable which specifically denotes the ability of the health care system to supply medical resources, based on the requirements of each diabetic population group and the total available medical resources in the South African health care system. This `Health care system workload` variable may equated to

$$\frac{a_1 \times \textit{Prediabetic population} + a_2 \times \textit{Diabetic population} + a_3 \times \textit{Diabetic complication population}}{\textit{Total available medical resources available in South African health care system}},$$

where a_1, a_2, and a_3 are equal to a constant proportion of resources utilised by a single prediabetic patient, diabetic patient, and diabetic patient with complications, respectively, and medical resources refers to the pharmaceuticals used by a patient and any time spent with a health care professional in a diabetic check-up. This `Health care system workload` variable would then be used as a driver to influence the availability of medical equipment and pharmaceuticals, the health care professional to patient ratio, and the implementation of screening and education interventions in the diabetic health care system of South Africa. Due to the unavailability of data needed to determine this variable, especially the total available medical resources in the South African health care system, this approach for determining the availability of resources is not suitable for the system dynamics model. Diabetic populations, therefore, remain the driver for the availability of resources within the diabetic health care system.

When considering the `Screening intervention` variable, it may be seen in Figure 5.4 that the variable is influenced by the screening of high-risk individuals, which is ultimately influenced by the `Diabetes proportion` variable. This is in-line with the CLD in Figure 5.1, where the diabetic populations influence the implementation of interventions — such as that of screening.

Prediabetes onset and recovery

In order to understand the process of prediabetes onset and recovery, the following stock and flows illustrated in Figure 5.2 are discussed:

I `Non-diabetic population` stock;

II `Number of undiagnosed prediabetics` stock;

III `Number of diagnosed prediabetics` stock;

IV `Undiagnosed prediabetes recovery` flow;

V `Prediabetes onset` flow; and

VI `Diagnosed prediabetes recovery` flow.

When considering the `Non-diabetic population` stock, an inflow of a `birth rate` flow and outflow of a `death rate` flow is observed, as shown in Figure 5.3. As discussed in §1.5, however, the population investigated is only an adult population. 'Births' in this case, refers only to a population inflow of adults. Furthermore, the `Non-diabetic population` stock has an outflow of a `Prediabetes onset` flow to the `Number of undiagnosed prediabetics` stock, which is due to a portion of the non-diabetic population developing undiagnosed prediabetes. Prediabetic onset will never begin in an undiagnosed state, but is rather diagnosed at a later stage. The `Non-diabetic population` stock also has two inflows, namely the `Undiagnosed prediabetes recovery` and `Diagnosed prediabetes recovery` flows from the `Number of undiagnosed prediabetics` and `Number of diagnosed prediabetics` stocks, respectively. These inflows are as a result of a portion of both the undiagnosed prediabetic and diagnosed prediabetic populations recovering from prediabetes and returning to the non-diabetic population. The `Non-diabetic population` stock, therefore, accumulates a stock in units *person* equal to

$$\begin{aligned} Integral(&Birth\ rate\ +\ Diagnosed\ diabetes\ recovery\ +\ Undiagnosed\ prediabetes\ recovery \\ &-\ Death\ \ rate\ -\ Prediabetes\ onset) + stock\ value\ at\ t_0. \end{aligned}$$

The sum of the stock is integrated so as to determine the accumulation of stock from t_0 to t_1, as described in §4.4.3.

When considering the `Number of undiagnosed prediabetics` stock, only one inflow is observed, as may be seen in Figure 5.3, namely the `Prediabetes onset` flow, which is as a result of a portion of the non-diabetic population developing prediabetes. In terms of outflows of the `Number of undiagnosed prediabetics` stock, the `Diagnosis prediabetes`, `Undiagnosed prediabetes recovery`, `Undiagnosed diabetes onset`, and `Death rate undiagnosed prediabetes` flows are observed.

The `Number of undiagnosed prediabetics` stock, therefore, accumulates a stock in units *person* equal to

$$\begin{aligned}&Integral(Prediabetes\ onset\ -\ Death\ rate\ undiagnosed\ prediabetes\ -\ Diagnosis\ prediabetes\\&\quad -\ Undiagnosed\ diabetes\ onset\ -\ Undiagnosed\ prediabetes\ recovery)\\&\quad +\ stock\ value\ at\ t_0.\end{aligned}$$

When considering the `Number of diagnosed prediabetics` stock, again only one inflow is observed, as may be seen in Figure 5.3, namely the `Diagnosis prediabetes` flow, which is as a result of the prediabetic diagnosis of a portion of the undiagnosed prediabetics population. In terms of outflows of the `Number of diagnosed prediabetics` stock, the `Diagnosed prediabetes recovery`, `Diabetes onset`, and `Death rate diagnosed prediabetes` flows are observed. The `Number of diagnosed prediabetics` stock, therefore, accumulates a stock in units *person* equal to

$$\begin{aligned}&Integral(Diagnosis\ prediabetes\ -\ Death\ rate\ diagnosed\ prediabetes\ -\ Diabetes\ onset\\&\quad -\ Diagnosed\ diabetes\ recovery)\ +\ stock\ value\ at\ t_0.\end{aligned}$$

As shown in Figure 5.2, the `Prediabetes onset` flow is influenced by the `Risk for diabetes and prediabetes` variable. According to Tabak [111], approximately 5–10% of people per year develop prediabetes. It may, therefore, be assumed that at least 5% of the `Non-diabetic population` stock will flow to the `Number of undiagnosed prediabetics` stock through the `Prediabetes onset` flow. In order for this 5% base value to be established, a constant variable `Prediabetes onset RATE` is used and is equal to a rate of 0.05 *person per year*. The `Risk for diabetes and prediabetes` variable, therefore, influences the modifiable 5% difference. The `Prediabetes onset` flow is, therefore, defined to operate at a rate of *person per year* equal to

$$\begin{aligned}&Normal\ glycemic\ level\ population \times (Prediabetes\ onset\ RATE + (Prediabetes\ onset\ RATE)\\&\quad \times Risk\ for\ diabetes\ and\ prediabetes),\end{aligned}$$

since the product of the rate of prediabetes onset and the number of non-diabetic population, in addition to the 5% base level of the population, results in the rate of undiagnosed prediabetics per year.

Similarly, the `Undiagnosed prediabetes recovery` flow is also influenced by the `Risk for diabetes and prediabetes` variable, and, according to Tabak [111], the same approximation of between 5–10% of people per year revert back to non-diabetic from prediabetes. The `Undiagnosed prediabetes recovery` flow is, therefore, defined to operate at a rate of *person per year* equal to

$$\begin{aligned}&Number\ of\ undiagnosed\ prediabetics \times (Prediabetes\ recovery\ RATE\\&\quad - (Prediabetes\ recovery\ RATE) \times\ Risk\ for\ diabetes\ and\ prediabetes),\end{aligned}$$

since the product of the rate of undiagnosed prediabetes recovery and the number of undiagnosed prediabetics, beginning at a maximum of 10% and removing those affected by the risk factors, results in the rate of undiagnosed recovering prediabetics per year. In order for this 10% maximum value to be established, a constant variable `Prediabetes recovery RATE` is used and is equal to a rate of 0.01 *person per year*.

Finally, as may be seen in Figure 5.2, the `Diagnosed prediabetes recovery` flow is influenced by both the `Risk for diabetes and prediabetes` and `Management of prediabetes` variables. The `Management of prediabetes` variable is a modifiable factor that promotes recovery from prediabetes and limits the onset of diabetes. Considering the aforementioned approximation that between 5–10% of people per year recover from prediabetes and revert to non-diabetic, the `Diagnosed prediabetes recovery` flow is, therefore, defined to operate at a rate of *person per year* equal to

$$\begin{aligned}&Number\ of\ diagnosed\ prediabetics\ \times (Prediabetes\ recovery\ RATE\\&-(Prediabetes\ recovery\ RATE \times\ Risk\ for\ diabetes\ and\ prediabetes)\\&+(Prediabetes\ recovery\ RATE\ \times\ Management\ of\ prediabetes)),\end{aligned}$$

since the product of the rate of diagnosed diabetes recovery and the number of diagnosed prediabetics, beginning at a maximum of 10% and removing those affected by the risk factors and adding those who received sufficient care in managing prediabetes, results in the rate of diagnosed recovering prediabetics per year. Again for this 10% maximum value to be established, the constant variable `Prediabetes recovery RATE` is used.

From Figure 5.2, it is shown that the obese proportion of the population plays a significant role in influencing the `Risk for diabetes and prediabetes` variable. In order to demonstrate the workings of the `Risk for diabetes and prediabetes` variable, an extract of the complete system dynamics stock and flow model is shown in Figure 5.5.

As discussed in §5.3.1, obesity is the leading modifiable risk factor for prediabetes, as well as being the leading modifiable risk factor for diabetes (for people with prediabetes) [41]. The risk of developing prediabetes and diabetes is, therefore, observed to be largely influenced by the obese proportion of the population, as may be seen in Figure 5.5. Although categorised with the other modifiable factors, the `Risk for diabetes and prediabetes` variable is not modifiable within this system dynamics stock and flow model. Since the obesity disease does not fall within the clinical stages of the diabetes disease, any interventions targeted at the management of the obese proportion of the population are not considered in this model.

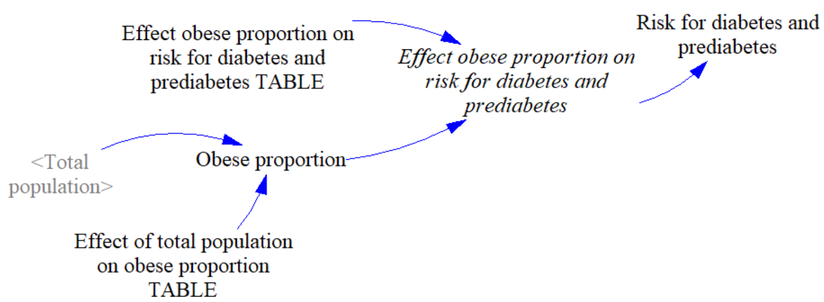


FIGURE 5.5: *Extract of the complete system dynamics stock and flow model demonstrating the risk for diabetes and prediabetes.*

From Figure 5.2, it may be seen that three modifiable factors influence the `Management of prediabetes` variable. As shown in Figure 5.1, the *Effect of healthy lifestyle education to prediabetics*, *Effect of self-management education on prediabetic patient self-management*, and the *Treatment procedure* modifiable variables influence the three diabetic populations independently, therefore, resulting in an or-logic relationship. It may, therefore, be shown that the `Management of prediabetes` variable operates at a rate of *dimentionless per year* equal to

$$
\begin{aligned}
&1 - (1 - Effect\,of\,healthy\,lifestyle\,education\,to\,prediabetics)\\
&\times (1 - Effect\,of\,self\,management\,education\,on\,prediabetic\,patient\,self\,management)\\
&\times (1 - Treatment\,procedure).
\end{aligned}
$$

In order to demonstrate the workings of the `Management of prediabetes` variable, an extract of the complete system dynamics stock and flow model is shown in Figure 5.6.

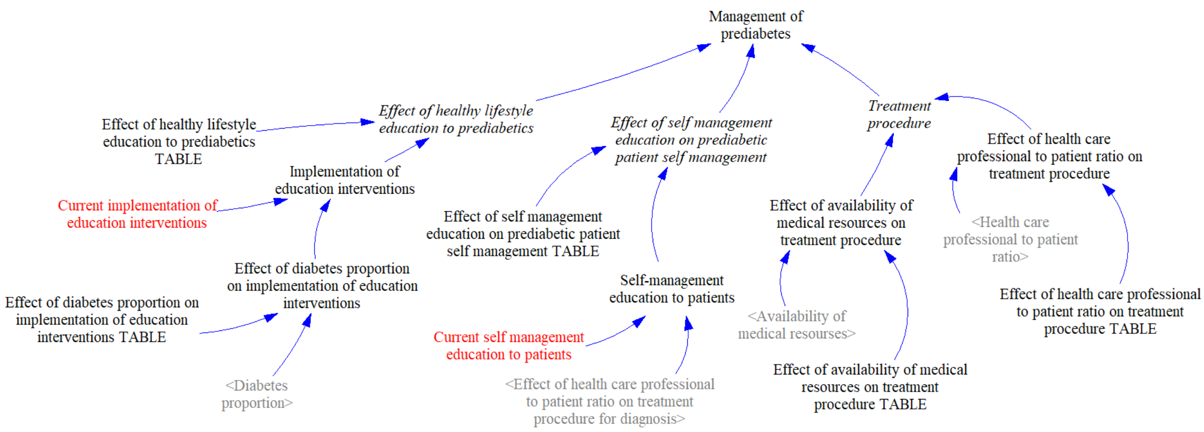


FIGURE 5.6: *Extract of the complete system dynamics stock and flow model demonstrating the management of prediabetes.*

When the `Effect of healthy lifestyle education to prediabetics` variable is considered, it may be seen in Figure 5.6 that the variable is influenced by the healthy lifestyle education to prediabetics, which is ultimately influenced by the `Diabetes proportion` variable. This is in-line with the CLD in Figure 5.1, where the diabetic populations influence the implementation of interventions — such as that of healthy lifestyle education. For the `Effect of self-management education on prediabetic patient self-management` in Figure 5.6, it may be observed that the that this variable is influenced by the self-management education to prediabetics, which is ultimately influenced by the health care professional to patient ratio. This is in-line with the CLD in Figure 5.1, where the implementation of self-management education influences the diabetic populations.

Finally, when considering the `Treatment procedure` variable, it may be seen in Figure 5.6 that the variable is influenced by the availability of medical resources and the health care professional to patient ratio, as discussed in the above *Diagnosis of prediabetes, diabetes and diabetes with complications* section. A similar equation may be derived for the `Treatment procedure` variable.

Diabetes Onset and Progression

In order to understand the process of diabetes onset and progression, the following stock and flows in Figure 5.2 are discussed:

I `Number of undiagnosed diabetics` stock;

II `Number of diagnosed diabetics` stock;

III `Number of undiagnosed diabetics with complications` stock;

IV `Number of diagnosed diabetics with complications` stock;

V `Undiagnosed diabetes progression` flow; and

VI `Diagnosed diabetes progression` flow.

When considering the `Number of undiagnosed diabetics` stock, two inflows are observed, as shown in Figure 5.3, namely the `Undiagnosed diabetes onset` and `Diabetes onset` flows, which are as a result of a portion of the undiagnosed and diagnosed prediabetic populations developing diabetes. In terms of outflows of the `Number of undiagnosed diabetics` stock, the `Diagnosis diabetes`, `Undiagnosed diabetes progression`, and `Death rate undiagnosed diabetics` flows are observed. The `Number of undiagnosed diabetics` stock, therefore, accumulates a stock in units *person* equal to

$$\begin{aligned}&Integral(Diabetes\ onset + Undiagnosed\ diabetes\ onset - Death\ rate\ undiagnosed\ diabetics\\&\quad - Diagnosis\ diabetes\ - Undiagnosed\ diabetes\ progression)\ + stock\ value\ at\ t_0.\end{aligned}$$

When considering the `Number of diagnosed diabetics` stock, two inflows are observed, as shown in Figure 5.3, namely the `Diagnosis diabetes` and `Diabetes onset` flows, which are as a result of the diabetic diagnosis of a portion of the undiagnosed diabetics population and a portion of the diagnosed prediabetic population developing diabetes, respectively. In terms of outflows of the `Number of diagnosed diabetics` stock, the `Diagnosed diabetes progression` and `Death rate diagnosed diabetes` flows are observed. The `Number of diagnosed diabetics` stock, therefore, accumulates a stock in units *person* equal to

$$\begin{aligned}&Integral(Diabetes\ onset + Diagnosis\ diabetes - Death\ rate\ diagnosed\ diabetics - Diagnosed\\&\quad diabetes\ progression) +\ stock\ value\ at\ t_0.\end{aligned}$$

When considering the `Number of undiagnosed diabetics with complications` stock, one inflow is observed, as shown in Figure 5.3, namely the `Undiagnosed diabetes progression flows`, which is as a result of a portion of the undiagnosed diabetic populations developing diabetic complications. In terms of outflows of the `Number of undiagnosed diabetics with complications` stock, the `Diagnosis diabetes with complications` and `Diagnosis diabetes with complications` flows are observed.

The `Number of undiagnosed diabetics with complications` stock, therefore, accumulates a stock in units *person* equal to

$$
\begin{aligned}
&Integral(Undiagnosed\ diabetes\ progression - Diagnosis\ diabetes\ with\ complications\\
&\quad - Undiagnosed\ deaths) + stock\ value\ at\ t_0.
\end{aligned}
$$

When considering the `Number of diagnosed diabetics with complications` stock, two inflows are observed, as shown in Figure 5.3, namely the `Diagnosis diabetes with complications` and `Diagnosed diabetes progression` flows, which are as a result of the diabetes with complications diagnosis of a portion of the undiagnosed diabetes with complications population and a portion of the diagnosed diabetic population developing diabetic complications, respectively. In terms of outflows of the `Number of diagnosed diabetics with complications` stock, the `Diagnosed deaths` flow is observed. The `Number of diagnosed diabetics with complications` stock, therefore, accumulates a stock in units *person* equal to

$$
\begin{aligned}
&Integral(Diagnosed\ diabetes\ progression + Diagnosis\ diabetes\ with\ complications\\
&\quad - Diagnosed\ deaths) +\ stock\ value\ at\ t_0.
\end{aligned}
$$

When considering the `Undiagnosed diabetes progression` flow, no modifiable factors are observed to influence the flow, as may be seen in Figure 5.2. The undiagnosed diabetes in this flow are still undiagnosed and are receiving no treatment that would limit the `Undiagnosed diabetes progression` flow. As discussed in §5.1.2, only fatal diabetic complications are considered when modelling the dynamics of diabetics with complications, as non-fatal diabetic complications do not affect the dynamics of the diabetic with complications population (*i.e.* the diabetic with complications death rate. Furthermore, heart disease accounts for up to 70% of all diabetic mortality, as discussed in §2.1.6. Since heart disease is the leading diabetic cause of death, in this model it is assumed that diabetic complications are caused by heart disease. Heart disease is responsible for almost one in six (or 17.3% of) deaths in South Africa [39]. The risk of heart disease in persons with type 2 diabetes is, however, increased 3-fold when compared to people without diabetes [103]. Since there is no publicly available data on the diabetes disease progression in South Africa [103], the undiagnosed diabetics are, therefore, assumed to develop complications at a rate of 51.9% of the number of undiagnosed diabetics per year. In order for this rate to be established, a constant variable `Diabetes progression RATE` is used and set equal to a rate of 0.519 *person per year*. The `Undiagnosed diabetes progression` flow is, therefore, defined to operate at a rate of *person per year* equal to

$$Number\ of\ undiagnosed\ diabetics \times (Diabetes\ progression\ RATE).$$

Similarly, the `Diagnosed diabetes progression` flow is also assumed to experience the development of diabetes complications at a rate of 0.519 *person per year* and the `Diabetes progression RATE` constant variable is used to establish this rate. The `Diagnosed diabetes progression` flow is, however, influenced by the `Management of diabetes` variable, as may be seen in Figure 5.2. The `Death rate diagnosed diabetics` flow is, therefore, defined to operate at a rate of *person per year* equal to

$$
\begin{aligned}
&Number\ of\ diagnosed\ diabetics \times (Diabetes\ progression\ RATE\\
&\quad - Diabetes\ progression\ RATE * Management\ of\ diabetes),
\end{aligned}
$$

since the product of the rate of diabetes complications progression of 0.519 *person per year* and the number of diagnosed diabetics, while removing the portion of the diagnosed diabetes receiving effective management of diabetes care, results in the rate of diagnosed diabetes complications progression per year.

In order to demonstrate the workings of the `Management of diabetes` variable, an extract of the complete system dynamics stock and flow model is shown in Figure 5.7.

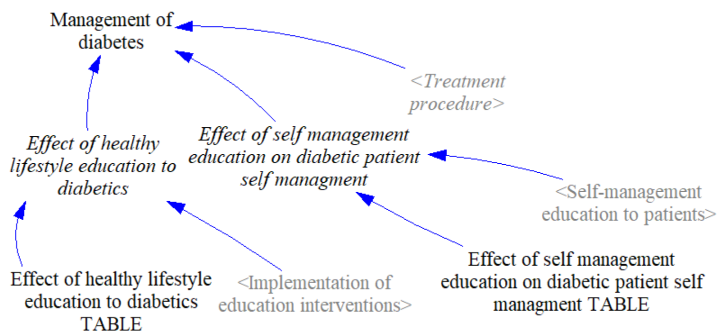


FIGURE 5.7: *Extract of the complete system dynamics stock and flow model demonstrating the management of diabetes.*

When the `Effect of healthy lifestyle education to diabetics` variable is considered, it may be seen in Figure 5.7 that the variable is influenced by the healthy lifestyle education to diabetics, which is ultimately influenced by the `Diabetes proportion` variable. This is in-line with the CLD in Figure 5.1, where the diabetic populations influence the implementation of interventions — such as that of healthy lifestyle education. For the `Effect of self-management education on diabetic patient self-management` in Figure 5.7, it may be observed that the variable is influenced by the self-management education to diabetics, which is ultimately influenced by the health care professional to patient ratio. This is in-line with the CLD in Figure 5.1, where the implementation of self-management education influences the diabetic populations. Finally, it may be seen in Figure 5.7, that the `Management of diabetes` variable is influenced by the `Treatment procedure` variable, which has been thoroughly discussed in the analysis of the `Management of prediabetes` variable.

5.3.3 Initial values and parameters

Summaries of the initial values and constants used in the system dynamics stock and flow model analysing the diabetes population dynamics in South Africa, as discussed in §5.3.2, are presented in Tables 5.2 and 5.3, respectively.

5.3.4 Model assumptions on non-linear relationships

While building a system dynamics model, the situation may arise where no simple algebraic equation exists to define a relationship between two variables. For example, the death rate of a population of rabbits in a fixed area increases rapidly as the area gets more crowded [107]. In these cases where the relationship between two variables is non-linear, table functions may be utilised to represent the relationship.

Table 5.2: *Summary of the initial values used in the system dynamics stock and flow model.*

Variable name	Variable type	Quantity	Unit	Validation
Normal glycemic level population	Stock	46 940 500	Person	With a South African population of 55.85 million [130], of which 7% are diabetic [152] and an addition 5 million are prediabetic [103], a non-diabetic population of 47.74 million is observed.
Number of undiagnosed prediabetics	Stock	4 500 000	Person	According to the South African DoH [103], 5 million South Africans are estimated to have prediabetes. The Centre for Disease Control and Prevention, however, reports that only 10% of prediabetics are diagnosed, therefore, totalling an undiagnosed prediabetic population of 500 000.
Number of diagnosed prediabetics	Stock	500 000	Person	According to the South African DoH [103], 5 million South Africans are estimated to have prediabetes. The Centre for Disease Control and Prevention, however, reports that only 10% of prediabetics are diagnosed, therefore, totalling an diagnosed prediabetic population of 4.5 million.
Number of undiagnosed diabetics	Stock	1 149 113	Person	With a South African population of 55.85 million [130], of which 7% are diabetic [152], there are an estimated 3.91 million diabetics in South Africa. 61.1% of all diabetics are, however, undiagnosed. Furthermore, diabetic complications currently affect 51.9% of all person with diabetes. There are, therefore, 1 149 113 undiagnosed diabetics without complications.
Number of diagnosed diabetics	Stock	731 596	Person	With a South African population of 55.85 million [130], of which 7% are diabetic [152], there are an estimated 3.91 million diabetics in South Africa. 61.1% of all diabetics are, however, undiagnosed. Furthermore, diabetic complications currently affect 51.9% of all person with diabetes. There are, therefore, 731 596 diagnosed diabetics without complications.
Number of undiagnosed diabetics with complications	Stock	1 239 896	Person	With a South African population of 55.85 million [130], of which 7% are diabetic [152], there are an estimated 3.91 million diabetics in South Africa. 61.1% of all diabetics are, however, undiagnosed. Furthermore, diabetic complications currently affect 51.9% of all person with diabetes. There are, therefore, 1 239 896 undiagnosed diabetics with complications.
Number of diagnosed diabetics with complications	Stock	789 393	Person	With a South African population of 55.85 million [130], of which 7% are diabetic [152], there are an estimated 3.91 million diabetics in South Africa. 61.1% of all diabetics are, however, undiagnosed. Furthermore, diabetic complications currently affect 51.9% of all person with diabetes. There are, therefore, 789 393 diagnosed diabetics with complications.

Table functions are typically preferred over complicated equations, as the shape, slopes and saturation points may be controlled so as to accurately represent the non-linear relationship between two variables [68, 107, 122]. In addition, table functions are also generally easier to interpret and visualise than complex, algebraic equations [68]. The relationship assumptions made in the table functions are generally based on mental models, literature and theory, expert opinion, and experience [68, 107, 122]. In the case of academic research, regression models are generally used within the table functions to demonstrate the causal effect relationship between the variables. As described in §1.5, however, the availably of data relating to various aspects of the diabetic health care, as well as regression models thereof, are significantly limited. Reasonable assumptions based on mental models and literature reviewed are, therefore, utilised so as to develop these table functions.

Throughout the development of the system dynamics stock and flow model, as shown in §5.3.3, lookup tables are utilised the in *Vensim DSS* software as table functions so as to make assumptions about the non-linear relationships exhibited between two variables. The use of a lookup function within a lookup table is similar to that of a predefined function that take one variable to produce an output variable, as in $output\ variable = lookup\ function\ name(input\ variable)$ [122].

TABLE 5.3: *Summary of the constants used in the system dynamics stock and flow model.*

Variable name	Variable type	Quantity	Unit	Validation
South African birth rate	Constant	0.0207	Dmnl/Year	According to the World Bank [128, 129], South Africa experiences 21 births per 1000 population.
South African life expectancy	Constant	62.77	Year	According to the World Bank [128, 129], 62.77 years is the average South African life expectancy.
Prediabetic life expectancy	Constant	62.77	Year	As the prediabetes disease is not fatal [103], the South African life expectancy may be expected for those with prediabetes.
Diabetic life expectancy	Constant	62.77	Year	As diabetes without complications is not fatal [103], the South African life expectancy may be expected for those with diabetes without complications.
Diabetic with complications life expectancy	Constant	52.77	Year	It is estimated that type 2 diabetes reduces life expectancy by 10 years [61]. With a South African life expectancy of 62.77 years, 52.77 years are expected for a diabetic with complications.
Prediabetes onset RATE	Constant	0.05	Person/Year	According to Tabak [111], approximately 5-10% of people per year develop prediabetes. The rate of prediabetes onset is, therefore, at least 5%.
Prediabetes recovery RATE	Constant	0.01	Person/Year	According to Tabak [111], 5-10% of people per year revert back to non-diabetic from prediabetes. The rate of prediabetes recovery is, therefore, a maximum of 10%.
Diabetes progression RATE	Constant	0.519	Person/Year	Heart disease is responsible for 17.3% of deaths in South Africa [39]. The risk of heart disease in persons with type 2 diabetes is, however, increased 3-fold when compared with people without diabetes [103]. Undiagnosed diabetics, therefore, develop diabetic complications at a rate of 51.9% of the number of undiagnosed diabetics per year or 0.519 *person per year*.

The following variables are used as lookup tables within the model so as to assume relationships between variables within the diabetic health care system within South Africa:

I `Effect of diabetes proportion on availability of medical resources TABLE` variable;

II `Effect of availability of medical resources on treatment procedure for diagnosis TABLE` variable;

III `Effect of diabetes proportion on health care professional to patient ratio TABLE` variable;

IV `Effect of health care professional to patient ratio on treatment procedure for diagnosis TABLE` variable;

V `Effect of diabetes proportion on implementation of screening intervention TABLE` variable;

VI `Effect of screening on diagnosis TABLE` variable;

VII `Effect of total population on obese proportion TABLE` variable;

VIII `Effect obese proportion on risk for diabetes and prediabetes TABLE` variable;

IX `Effect of diabetes proportion on implementation of education interventions TABLE` variable;

X `Effect of healthy lifestyle education to prediabetics TABLE` variable;

XI `Effect of self-management education on prediabetic patient self-management TABLE` variable;

XII `Effect of availability of medical resources on treatment procedure TABLE` variable;

XIII `Effect of health care professional to patient ratio on treatment procedure TABLE` variable;

XIV `Effect of healthy lifestyle education to diabetics TABLE` variable; and

XV `Effect of self-management education on diabetic patient self-management TABLE` variable.

In the sections to follow, the aforementioned variables are described, and their respective lookup table are shown and reasoned.

Lookup table on the effect of diabetes proportion on availability of medical resources

In the `Effect of diabetes proportion on availability of medical resources TABLE` variable, as shown in Figure 5.4, a lookup table is used to assume the relationship of the diabetes proportion on the availability of medical resources. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.8.

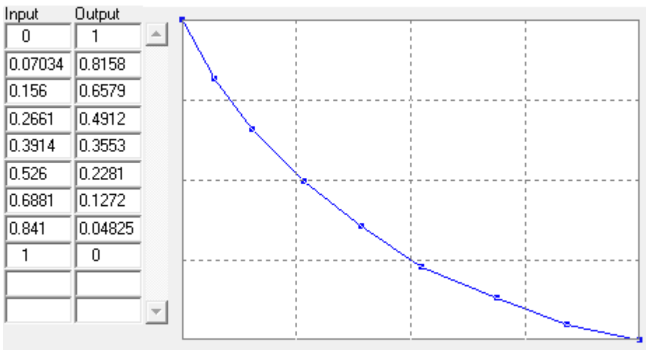


FIGURE 5.8: *Lookup table on the effect of diabetes proportion on availability of medical resources.*

The `Effect of diabetes proportion on availability of medical resources TABLE` variable considers the diabetes proportion as an input to determine the availability of medical resources. It is reasonable to assume that as the diabetes proportion of the population increases, more medical equipment and pharmaceuticals are used, thereby decreasing the available medical resources. The *Decision-Making Rule* (DMR) or graphical assumption in the lookup table is, therefore, as the diabetes proportion increases to 100%, the availability of medical resources decreases up to an effect just above 0%.

Lookup table on the effect of availability of medical resources on treatment procedure for diagnosis

In the `Effect of availability of medical resources on treatment procedure for diagnosis TABLE` variable, as shown in Figure 5.4, a lookup table is used to assume the relationship of the availability of medical resources on the treatment procedure for diagnosis. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.9.

The `Effect of availability of medical resources on treatment procedure for diagnosis TABLE` variable considers the availability of medical resources as an input to determine the effect of the treatment procedure for diagnosis. It is reasonable to assume that as

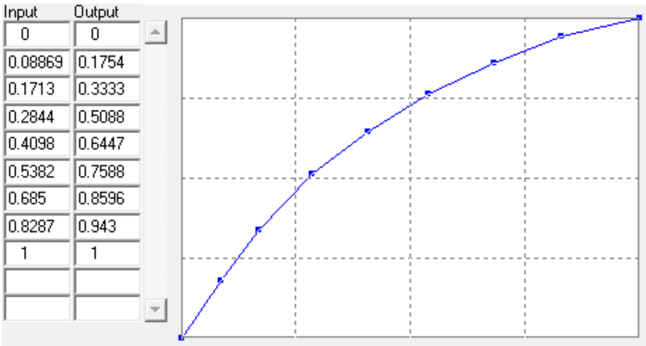


FIGURE 5.9: *Lookup table on the effect of availability of medical resources on treatment procedure for diagnosis.*

the availability of medical resources increases, more resources are available to ensure the effectiveness of the treatment procedure, which increases the effect of the treatment procedure for diagnosis. The DMR or graphical assumption in the lookup table is, therefore, as the availability of medical resources increases to 100%, the effect of the treatment procedure for diagnosis also increases up to an effect of 100%. This graphical assumption, however, follows a logarithmic function so as to demonstrate the necessity of medical resources in the treatment procedure for diagnosis. Even when a small increase in the availability of medical resources is observed, the effect on the treatment procedure for diagnosis significantly increases.

Lookup table on the effect of diabetes proportion on health care professional to patient ratio

In the `Effect of diabetes proportion on health care professional to patient ratio TABLE` variable, as shown in Figure 5.4, a lookup table is used to assume the relationship of the diabetes proportion on the health care professional to patient ratio. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.10.

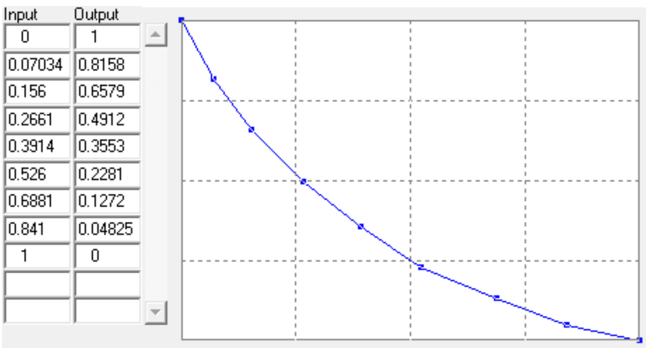


FIGURE 5.10: *Lookup table on the effect of diabetes proportion on health care professional to patient ratio.*

The `Effect of diabetes proportion on health care professional to patient ratio TABLE` variable considers the diabetes proportion as an input to determine the health care professional to patient ratio. It is reasonable to assume that as the diabetes proportion of the population increases and the number of health care professionals remain constant, the health care professional to patient ratio decreases. The DMR or graphical assumption in the lookup table is, therefore, as the diabetes proportion increases to 100%, the health care professional to patient ratio decreases up to an effect just above 0%.

Lookup table on the effect of health care professional to patient ratio on treatment procedure for diagnosis

In the `Effect of health care professional to patient ratio on treatment procedure for diagnosis TABLE` variable, as shown in Figure 5.4, a lookup table is used to assume the relationship of the health care professional to patient ratio on the treatment procedure for diagnosis. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.11.

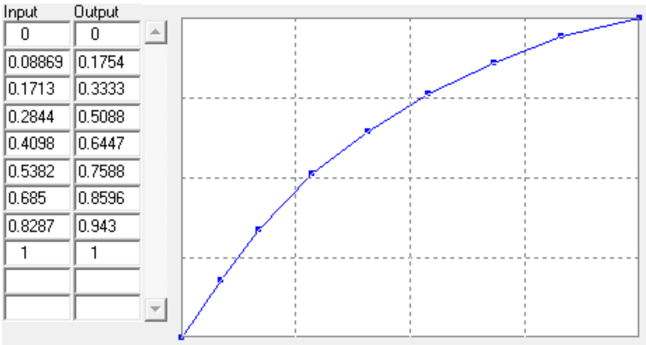


FIGURE 5.11: *Lookup table on the effect of health care professional to patient ratio on treatment procedure for diagnosis.*

The `Effect of health care professional to patient ratio on treatment procedure for diagnosis TABLE` variable considers the health care professional to patient ratio as an input to determine the effect of the treatment procedure for diagnosis. It is reasonable to assume that as the health care professional to patient ratio increases, more health care professionals are available to ensure the effectiveness of the treatment procedure, which increases the effect of the treatment procedure for diagnosis. The DMR or graphical assumption in the lookup table is, therefore, as the health care professional to patient ratio increases to 100%, the effect of the treatment procedure for diagnosis also increases up to an effect of 100%. This graphical assumption, however, follows a logarithmic function so as to demonstrate the necessity of health care professionals in the treatment procedure for diagnosis. Even when a small increase in the health care professional to patient ratio is observed, the effect on the treatment procedure for diagnosis significantly increases.

Lookup table on the effect of diabetes proportion on implementation of screening intervention

In the `Effect of diabetes proportion on implementation of screening intervention TABLE` variable, as shown in Figure 5.4, a lookup table is used to assume the relationship of the diabetes proportion on the implementation of screening interventions. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.12.

The `Effect of diabetes proportion on implementation of screening intervention TABLE` variable considers the diabetes proportion as an input to determine the implementation

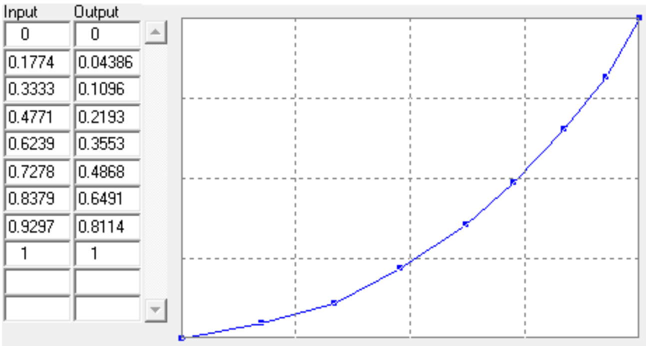


FIGURE 5.12: *Lookup table on the effect of diabetes proportion on implementation of screening intervention.*

of screening interventions. It is reasonable to assume that as the diabetes proportion of the population increases, there is an increased need to screen more high-risk individuals, which increases the number of screening interventions. The DMR or graphical assumption in the lookup table is, therefore, as the diabetes proportion increases to 100%, the implementation of screening interventions also increases up to an effect of 100%.

Lookup table on the effect of screening on diagnosis

In the `Effect of screening on diagnosis TABLE` variable, as shown in Figure 5.4, a lookup table is used to assume the relationship of the screening intervention on the diagnosis of prediabetes and diabetes. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.13.

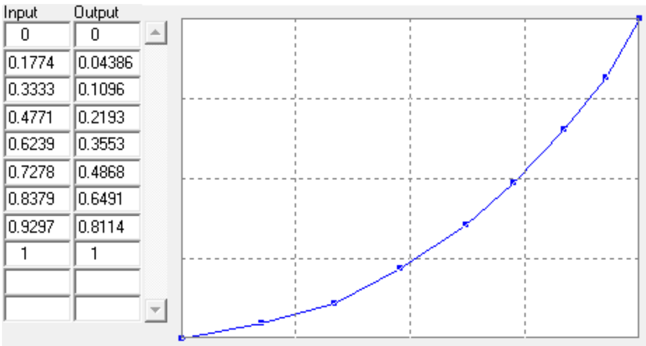


FIGURE 5.13: *Lookup table on the effect of screening on diagnosis.*

The `Effect of screening on diagnosis TABLE` variable considers the effect of the screening intervention as an input to determine the diagnosis of prediabetes and diabetes. It is reasonable to assume that as the screening intervention increases, more prediabetics and diabetes are diagnosed. The DMR or graphical assumption in the lookup table is, therefore, as the screening interventions increase to 100%, the diagnosis of prediabetics and diabetics also increases up to an effect of 100%.

Lookup table on the effect of total population on obese proportion

In the `Effect of total population on obese proportion TABLE` variable, as shown in Figure 5.6, a lookup table is used to assume the relationship of the total obese proportion of the South African population. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.14.

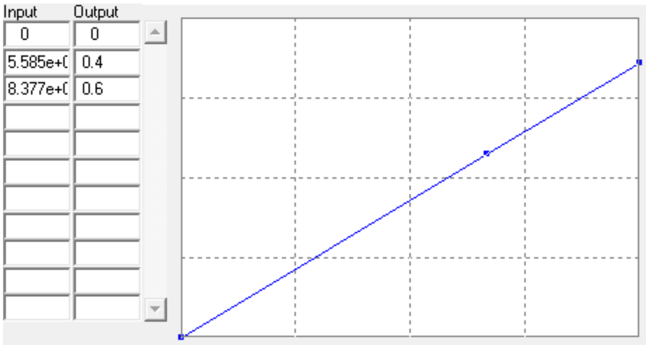


FIGURE 5.14: *Lookup table on the effect of total population on obese proportion.*

The `Effect of total population on obese proportion TABLE` variable considers the total South African population as an input to determine the obese proportion of the country. It is reasonable to assume that as the South African population increases, the obese proportion also increases. Currently, with a South African population of 55.85 million [130], approximately 40% of South African's are overweight or obese [21]. The DMR or graphical assumption in the lookup table is, therefore, as the South African population increases to 100%, the diagnosis of prediabetics and diabetics also increases up to an effect of 60% — which is in-line with Cois's prediction of a maximum percentage of those being overweight or obese [21].

Lookup table on the effect obese proportion on risk for diabetes and prediabetes

In the `Effect obese proportion on risk for diabetes and prediabetes TABLE` variable, as shown in Figure 5.6, a lookup table is used to assume the relationship of the obese proportion of South Africa on risk for diabetes and prediabetes. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.15.

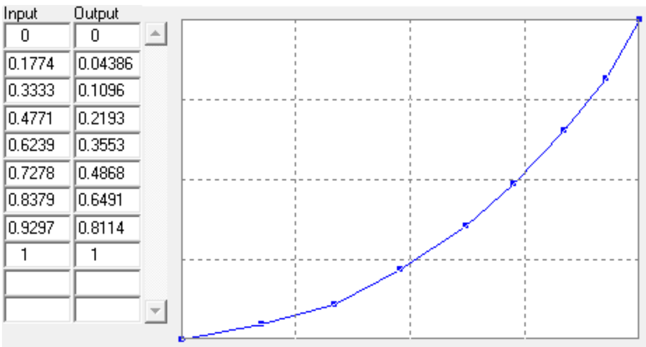


FIGURE 5.15: *Lookup table on the effect obese proportion on risk for diabetes and prediabetes.*

The `Effect obese proportion on risk for diabetes and prediabetes TABLE` variable considers the obese proportion of South Africa as an input to determine risk for diabetes and prediabetes. It is reasonable to assume that as the obese proportion increases, more non-diabetics and prediabetics are at risk to develop prediabetes and diabetes, respectively, due to obesity being the largest risk factor for prediabetic and diabetic onset. The DMR or graphical assumption in the lookup table is, therefore, as the obese proportion increases to 100%, the risk for diabetes and prediabetes also increases up to an effect of 100%.

Lookup table on the effect of diabetes proportion on implementation of education interventions

In the `Effect of diabetes proportion on implementation of education interventions TABLE` variable, as shown in Figure 5.6, a lookup table is used to assume the relationship of the diabetes proportion on the implementation of education interventions. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.16.

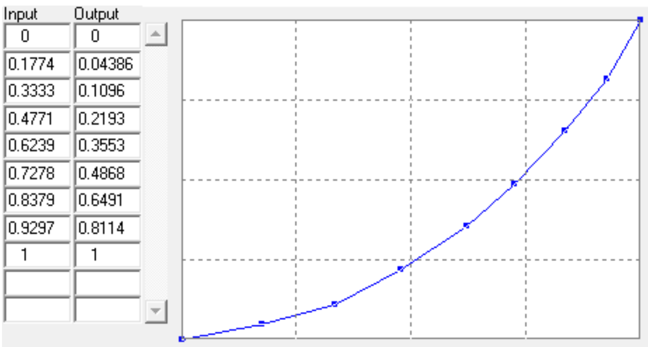


FIGURE 5.16: *Lookup table on the effect of diabetes proportion on implementation of education interventions.*

The `Effect of diabetes proportion on implementation of education interventions TABLE` variable considers the diabetes proportion as an input to determine the implementation of education interventions. It is reasonable to assume that as the diabetes proportion of the population increases, there is an increased need to educate regarding healthy lifestyle factors, which increases the implementation of education interventions. The DMR or graphical assumption in the lookup table is, therefore, as the diabetes proportion increases to 100%, the implementation of education interventions also increases up to an effect of 100%.

Lookup table on the effect of healthy lifestyle education to prediabetics

In the `Effect of healthy lifestyle education to prediabetics TABLE` variable, as shown in Figure 5.6, a lookup table is used to assume the relationship of the implementation of healthy lifestyle education interventions on the management of the prediabetic populations. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.17.

The `Effect of healthy lifestyle education to prediabetics TABLE` variable considers the implementation of healthy lifestyle education interventions as an input to determine the management of the prediabetic populations. It is reasonable to assume that as the implementation of healthy lifestyle education interventions increases, there is an increased prevalence of

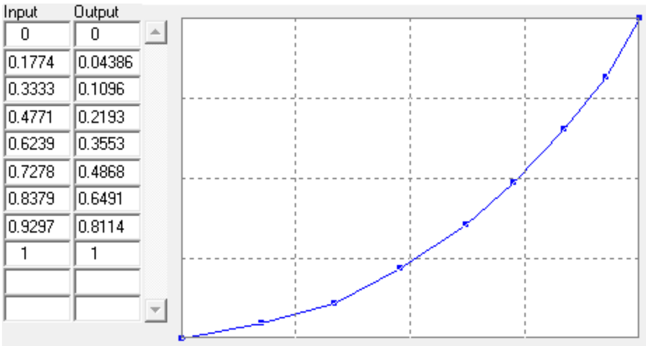


FIGURE 5.17: *Lookup table on the effect of healthy lifestyle education to prediabetics.*

healthy lifestyle factors, which increases the management of the prediabetic populations. The DMR or graphical assumption in the lookup table is, therefore, as the implementation of healthy lifestyle education interventions increases to 100%, the management of the prediabetic populations also increases up to an effect of 100%.

Lookup table on the effect of self-management education on prediabetic patient self-management

In the `Effect of self-management education on prediabetic patient self-management TABLE` variable, as shown in Figure 5.6, a lookup table is used to assume the relationship of the implementation of self-management education on prediabetic patient self-management. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.18.

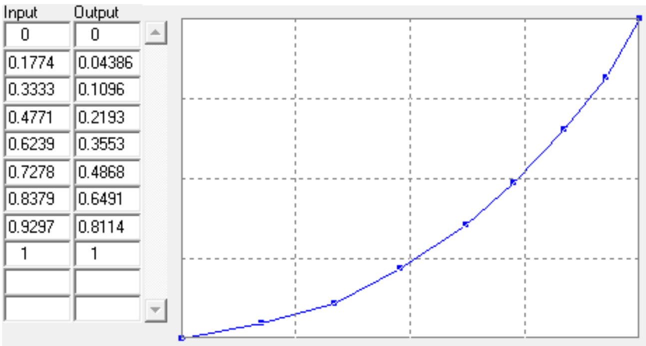


FIGURE 5.18: *Lookup table on the effect of self-management education on prediabetic patient self-management.*

The `Effect of self-management education on prediabetic patient self-management TABLE` variable considers the implementation of self-management education as an input to determine prediabetic patient self-management. It is reasonable to assume that as the implementation of self-management education increases, there is an increased prevalence of self-management education, which increases the prediabetic patient self-management. The DMR or graphical assumption in the lookup table is, therefore, as the implementation of self-management education increases to 100%, the prediabetic patient self-management also increases up to an effect of 100%.

Lookup table on the effect of availability of medical resources on treatment procedure

In the `Effect of availability of medical resources on treatment procedure TABLE` variable, as shown in Figure 5.6, a lookup table is used to assume the relationship of the availability of medical resources on the treatment procedure. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.19.

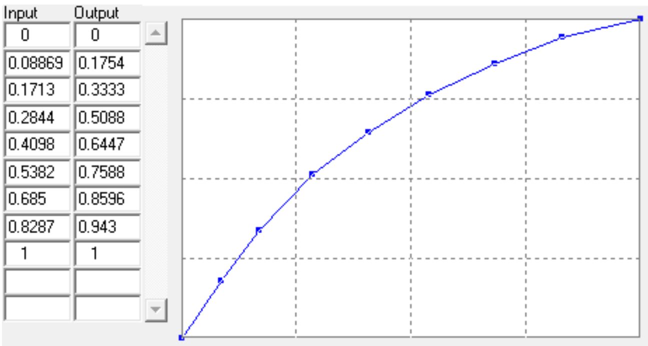


FIGURE 5.19: *Lookup table on the effect of availability of medical resources on treatment procedure.*

The `Effect of availability of medical resources on treatment procedure TABLE` variable considers the availability of medical resources as an input to determine the effect of the treatment procedure. It is reasonable to assume that as the availability of medical resources increases, more resources are available to ensure the effectiveness of the treatment procedure, which increases the effect of the treatment procedure. The DMR or graphical assumption in the lookup table is, therefore, as the availability of medical resources increases to 100%, the effect of the treatment procedure also increases up to an effect of 100%. This graphical assumption, however, follows a logarithmic function so as to demonstrate the necessity of medical resources in the treatment procedure. Even when a small increase in the availability of medical resources is observed, the effect on the treatment procedure significantly increases.

Lookup table on the effect of health care professional to patient ratio on treatment procedure

In the `Effect of health care professional to patient ratio on treatment procedure TABLE` variable, as shown in Figure 5.6, a lookup table is used to assume the relationship of the health care professional to patient ratio on the treatment procedure. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.20. The `Effect of health care professional to patient ratio on treatment procedure TABLE` variable considers the health care professional to patient ratio as an input to determine the effect of the treatment procedure. It is reasonable to assume that as the health care professional to patient ratio increases, more health care professionals are available to ensure the effectiveness of the treatment procedure, which increases the effect of the treatment procedure. The DMR or graphical assumption in the lookup table is, therefore, as the health care professional to patient ratio increases to 100%, the effect of the treatment procedure also increases up to an effect of 100%. This graphical assumption, however, follows a logarithmic function so as to demonstrate the necessity of health care professionals in the treatment procedure. Even when a small increase in the health care professional to patient ratio is observed, the effect on the treatment procedure significantly increases.

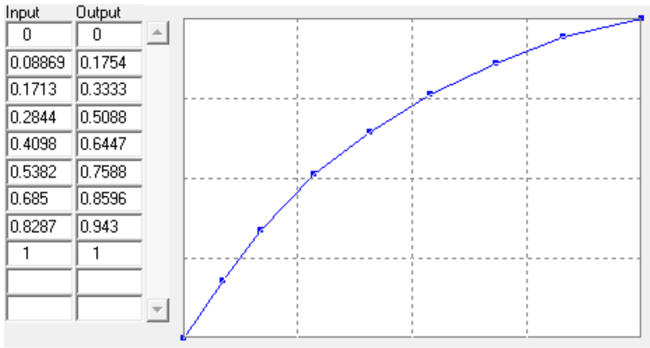


FIGURE 5.20: *Lookup table on the effect of health care professional to patient ratio on treatment procedure.*

Lookup table on the effect of healthy lifestyle education to diabetics

In the `Effect of healthy lifestyle education to diabetics TABLE` variable, as shown in Figure 5.7, a lookup table is used to assume the relationship of the implementation of healthy lifestyle education interventions on the management of the diabetic populations. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.21.

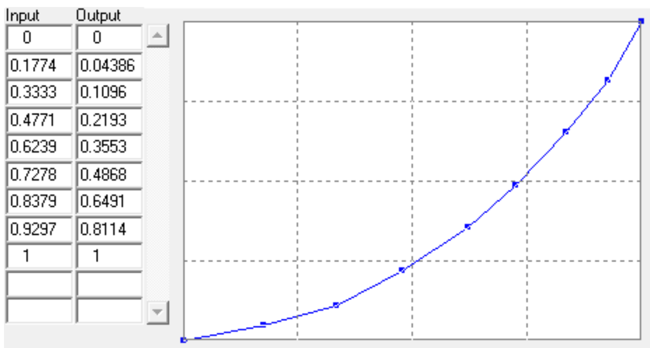


FIGURE 5.21: *Lookup table on the effect of healthy lifestyle education to diabetics.*

The `Effect of healthy lifestyle education to diabetics TABLE` variable considers the implementation of healthy lifestyle education interventions as an input to determine the management of the diabetic populations. It is reasonable to assume that as the implementation of healthy lifestyle education interventions increases, there is an increased prevalence of healthy lifestyle factors, which increases the management of the diabetic populations. The DMR or graphical assumption in the lookup table is, therefore, as the implementation of healthy lifestyle education interventions increases to 100%, the management of the diabetic populations also increases up to an effect of 100%.

Lookup table on the effect of self-management education on diabetic patient self-management

In the `Effect of self-management education on diabetic patient self-management TABLE` variable, as shown in Figure 5.7, a lookup table is used to assume the relationship of the implementation of self-management education on diabetic patient self-management. The graphical representation of the assumption on the relationship between the two variables is shown in Figure 5.22. The `Effect of self-management education on diabetic patient self-management TABLE` variable considers the implementation of self-management education as an input to determine diabetic patient self-management. It is reasonable to assume that as the implementation of self-management education increases, there is an increased prevalence of self-management education, which increases the diabetic patient self-management. The DMR or graphical assumption in the lookup table is, therefore, as the implementation of self-management education increases to 100%, the diabetic patient self-management also increases up to an effect of 100%.

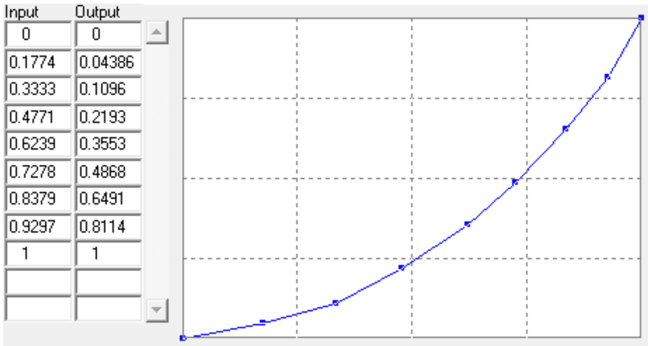


FIGURE 5.22: *Lookup table on the effect of self-management education on diabetic patient self-management.*

5.3.5 Decision variables for points of intervention

Throughout the development of the system dynamics stock and flow model, as shown in §5.3.3, key decision or leverage points were identified so as to allow for the testing of intervention strategies for the management of diabetes in South Africa. Variables were added to these decision points to allow for modifiable changes in the model during scenario analysis. These decision point variables include:

I `Current health care professional to patient ratio` variable;

II `Current screening of high risk individuals` variable;

III `Current availability of medical resources` variable;

IV `Current implementation of education interventions`; and

V `Current self-management education to patients` variable.

The `Current health care professional to patient ratio` decision variable influences the `Health care professional to patient ratio` variable, as shown in Figure 5.4. When the `Current health care professional to patient ratio` decision variable is increased or decreased, the health care professional to patient ratio of the system increases or decreases, respectively. This decision variable modifies the `Health care professional to patient ratio` variable by symbolically either "adding" or "removing" health care professionals to or from the system so as to determine the effect of modifying the health care professional to patient ratio on the management of the diabetes population dynamics.

The `Current screening of high risk individuals` decision variable influences the `Screening of high risk individuals` variable, as shown in Figure 5.4. When the `Current screening of high risk individuals` decision variable is increased or decreased, the screening opportunities of the diabetes disease in the system increases or decreases, respectively. This decision variable modifies the `Screening of high risk individuals` variable by symbolically either increasing or decreasing the number of screening intervention opportunities in the system so as to determine the effect of modifying the number of diabetes screening opportunities on the management of the diabetes population dynamics.

The `Current availability of medical resources` decision variable influences the `Availability of medical resources` variable, as shown in Figure 5.4. When the `Current availability of medical resources` decision variable is increased or decreased, the medical equipment and pharmaceuticals needed to treat the diabetes disease in the system increases or decreases, respectively. This decision variable modifies the `Availability of medical resources` variable by symbolically either increasing or decreasing the diabetes medical equipment and pharmaceuticals needed to treat the diabetes disease in the system so as to determine the effect of modifying the availability of medical equipment and pharmaceuticals on the management of the diabetes population dynamics.

The `Current implementation of education interventions` decision variable influences the `Implementation of education interventions` variable, as shown in Figure 5.6. When the `Current implementation of education interventions` decision variable is increased or decreased, the education interventions to promote healthy lifestyle factors in the system increases or decreases, respectively. This decision variable modifies the `Implementation of education interventions` variable by symbolically either increasing or decreasing the healthy lifestyle education interventions to manage the disease in the system so as to determine the effect of modifying the number of opportunities for healthy lifestyle education interventions on the management of the diabetes population dynamics.

The `Current self-management education to patients` decision variable influences the `Self-management education to patients` variable, as shown in Figure 5.6. When the `Current self-management education to patients` decision variable is increased or decreased, the self-management education to patients in the system increases or decreases, respectively. This decision variable modifies the `Self-management education to patients` variable by symbolically either increasing or decreasing the self-management education to patients in the system so as to determine the effect of modifying the opportunities for self-management education on the management of the diabetes population dynamics.

5.3.6 *Vensim DSS* model settings

The modelling setting utilised in the *Vensim DSS* system dynamics model is displayed in Figure 5.23. The modelling settings illustrate that the model is simulated over the fixed time period from 2014 to 2030 (as discussed in §5.1.2) using the time set unit of *Year*. The Euler method was selected as the integration type due to the method's ability to provide the approximate values of a solution for first order differential equations using time steps. Finally, a time step equal to 0.0625 serves as the delay fraction between iterations, which is slight less than a month.

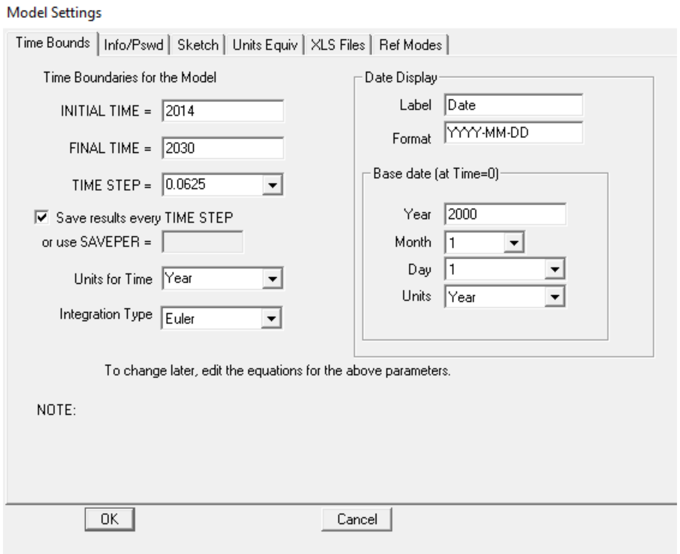


FIGURE 5.23: *VENSIM DSS model settings.*

5.4 Model verification and validation

As discussed in §4.4.4, system dynamics has typically been criticised for its lack of formal and quantitative validation and evaluation tools [9, 107]. Despite the difficulty in verification and validation, it is the responsibility of the modeller ensure that the best model has been developed with the information at hand.

The system dynamics model shown in §5.3 was iteratively verified throughout the process of model development using the verification method defined by Pruyt [89], as discussed in §4.4.4. The twelve points in the "Model Correctness Checklist" by Lai and Wahba, also discussed in §5.3, were also evaluated so as to verify the build of the model as follows:

1. *Units check* — The *Vensim DSS* built-in unit-checking feature was utilised to check all equations for consistency in units.

2. *Naming variables* — As a general naming convention, Ventana, the developers of Vensim, proposed that all variable names used in the model should clearly explain what a model element represents and should be used consistently. This may be observed in Figures 5.3, 5.4, 5.5, 5.6, and 5.7, where the system dynamics model variables are shown.

3. *No constants embedded in equations* — Constants used within the system dynamics model are assigned to model constant variables and are presented in Table 5.3. These constant variables are used within equations to prevent embedding constants within equations.

4. *Mention parameter values in the documentation* — All model parameter and initial values, as well as constant values, are presented in Tables 5.2 and 5.3, respectively, so as to document and reason the parameter values used within the model.

5. *Choose appropriately small time steps* — The Euler method was selected as the integration type due to the method's ability to provide the approximate values of a solution fo first order differential equations using time steps, as shown in §5.3.6. A time step equal to 0.0625 was then selected to serve as the delay fraction between iterations. This time step

is slightly less then a month than a month, which would be an appropriate time step to observe the effect policy interventions would have on the diabetic population month-to-month.

6. *Stock values can be changed only by flows* — As shown in Figure 5.3 and described in §5.3.2, all stocks are only altered and changed by the flows within the model.

7. *Every flow should be connected to a stock* — As shown in Figure 5.3, each flow of the model is connected to at least one stock.

8. *Flows should not be linked to auxiliary variables or to other flows* — As shown in Figure 5.3, no flows are linked to auxiliary variables or to another flow.

9. *Stocks should not be linked to stocks* — As shown in Figure 5.3, no stock to the model is linked to another stock.

10. *The use of IF THEN ELSE, MIN/MAX and other logic statements* — Real-world situations do generally most of the not behave according to IF THEN ELSE or MIN/MAX statements [60]. Change is typically gradual and not sudden, as suggested by the function. Lai and Wahba [60] suggest the use of table functions to avoid discontinuities introduced by the aforementioned statements. The use of tables functions is observed in §5.3.4, where the non-linear relationships within the model are assumed.

11. *Use of initial values* — The initial values within the model are clearly defined and reasoned in Table 5.2.

12. *Curving connectors* — Although largely reasoned for aesthetics, as well as to more easily trace feedback loops, curving connectors may be observed in Figures 5.4, 5.5, 5.6, and 5.7 of the system dynamics model.

As discussed in §4.4.4, model validation is referred to as the process of determining whether or not a model meets the objectives of the modelling study. The three forms of validation tests (as discussed in §4.4.4) consist of (i) direct structure tests, (ii) structure-oriented behaviour tests, and (iii)behaviour pattern tests.

Forrester and Senge developed specific validation tests based on the three aforementioned forms of validation tests. Sterman's textbook titled "Business dynamics: Systems thinking and modelling for a complex world" [107] may be consulted for a detailed explanation of each validation test, as well as the potential methods available for testing. The method and extent of each test applied to the system dynamics model is listed in Table 5.4, where model results may be found in Appendix A.

Table 5.4: *Validation tests performed on system dynamics model.*

Tests	Methods and degree of implementation
Boundry adequacy	Inspection of causal diagrams, stock and flow maps, and direct inspection of model equations to determine boundary adequacy.
Structural assessment	Inspection of causal diagrams, stock and flow maps, and direct inspection of model equations to assess model structure.
Dimensional consistency	Vensim DSS software dimensional analysis function. Inspection of model equations for suspect parameters to determine dimensional consistency.
Parameter assessment	Parameters assessed based on subject-matter expert opinion.
Extreme conditions	Inspection of each model equation. Testing the model response to extreme values of each input, as shown in Appendix A.1.
Integration error	Time step is cut in half and tested for changes in behaviour, in addition to using different integration methods, as shown in Appendix A.2.
Behaviour reproduction	Qualitative comparison between model output and behaviour of the real-world system is shown in Appendix A.3.

5.5 Chapter 5 conclusion

Chapter 5 aimed to use the system dynamics modelling approach to develop a system dynamics model to investigate the effects of existing intervention strategies on the management of diabetes in South Africa, in fulfilment of Research Objective IV. This chapter began by articulating the problem of the diabetic health care system in South Africa, followed by the presentation of a dynamic hypothesis in the form of a CLD so as to illustrate the hypothesised behaviour of the diabetic health care system. The CLD was subsequently used to design and develop a stock and flow model of the diabetic health care in South Africa, using the *Vensim DSS* software. Finally, the system dynamics model was verified and validated so as to establish the validity of the model, as well as to deem the model outputs to be accurate and credible, in fulfilment of Research Objective V. The verified and validated system dynamics model is used in Chapter 6 to obtain scenario results for the purpose of developing South African diabetic policy considerations.

CHAPTER 6

System dynamics model results

Contents

As discussed at the onset of Chapter 5, the aim of Part II of this research is to use the system dynamics modelling approach to develop a system dynamics model so as to investigate the effects of intervention strategies on the management of diabetes in South Africa. Following the development of the system dynamics model in Chapter 5, Chapter 6 aims to meet the aforementioned aim of Part II of this research by using the system dynamics model to investigate the policy intervention strategies through scenario testing and analysis so as to develop policy considerations.

At the onset of Chapter 6, the policy intervention scenarios are first defined, followed by the scenario testing results of the system dynamics model, in fulfilment of Research Objective VI. The scenario testing results are first presented in a solution space viewpoint of a single-objective problem where the aim is to minimise the total diabetic deaths per year, and then presented in the solution space viewpoint of a bi-objective problem, where the aim is to minimise both the undiagnosed and diagnosed diabetic deaths per year. To say, however, that this research is exclusively single or bi-objective is not correct, rather the aim of presenting both these viewpoints is to visualise the scenario results in alternative solution spaces that are both equally valid so as to identify scenarios worthy of consideration. Following the identification of notable scenarios, these scenarios, as well as the interventions applied for the specific scenario, are discussed so as to determine the aspects of the scenario that impacts the undiagnosed and diagnosed diabetic deaths per year. Finally, policy considerations are made so as to address the management of the diabetes disease in South Africa, in fulfilment of Research Objective VII.

6.1 Scenario testing of model

Scenario testing is a vital component of the system dynamics modelling approach in identifying the effectiveness of alternative diabetic policy intervention strategies though the running of model tests and scenarios. In this section, scenarios are first defined according to possible alternative diabetic intervention strategies. Thereafter, existing interventions for diabetic policy formulation are tested in the form of 'scenarios' so as to determine the most effective interventions to manage diabetes.

6.1.1 Scenario definitions

Scenario testing allows for alternative intervention strategies to be tested by selecting a single appropriate internal variable and changing this variable in varying proportions based on possible policy recommendations. In order to conduct scenario testing of the system dynamics model, scenarios first need to be developed and defined, as discussed in §4.4.1. As discussed in §5.3.5, five points of policy intervention were identified so as to allow for the testing of intervention strategies for the management of diabetes in South Africa, which include:

I `Current health care professional to patient ratio` variable;

II `Current screening of high risk individuals` variable;

III `Current availability of medical resources` variable;

IV `Current implementation of education interventions` variable; and

V `Current self-management education to patients` variable.

Decision point variable `Current health care professional to patient ratio` is translated into an intervention directed at varying the health care professional to patient ratio in the health care system and is referred to as *Health care professional to patient ratio Intervention*. For the sake of simplicity, this intervention is abbreviated to *HCPP*. A summary of the remaining decision point variables, and their translations to interventions and associated abbreviations, is shown in Table 6.1.

TABLE 6.1: *Summary of the decision point variables and their respective intervention.*

Decision point variable	**Intervention**	**Abbreviation**
Current health care professional to patient ratio	Health care professional to patient ratio intervention	HCPP
Current screening of high risk individuals	Screening intervention	SI
Current availability of medical resources	Availability of medical resources intervention	AMR
Current implementation of education interventions	Lifestyle education intervention	LEI
Current self-management education to patients	Self-management education intervention	SMEI

Given the aforementioned decision point variables, scenarios for testing are subsequently defined. The first scenario denotes the 'baseline' of the system — the case in which no interventions are applied. Five scenario are, therefore, defined to test the effects of the five individual interventions shown in Table 6.1. Combinations of interventions are also tested — first in every two

TABLE 6.2: *Scenarios defined for scenario testing.*

Scenario number	**Scenario name**	**Interventions applied**				
1	Baseline	—	—	—	—	—
2	Health care professional to patient ratio intervention	HCPP	—	—	—	—
3	Screening intervention	SI	—	—	—	—
4	Availability of medical resources intervention	AMR	—	—	—	—
5	Lifestyle education intervention	LEI	—	—	—	—
6	Self-management education intervention	SMEI	—	—	—	—
7	Combination intervention 1	HCPP	SI	—	—	—
8	Combination intervention 2	HCPP	AMR	—	—	—
9	Combination intervention 3	HCPP	LEI	—	—	—
10	Combination intervention 4	HCPP	SMEI	—	—	—
11	Combination intervention 5	SI	AMR	—	—	—
12	Combination intervention 6	SI	LEI	—	—	—
13	Combination intervention 7	SI	SMEI	—	—	—
14	Combination intervention 8	AMR	LEI	—	—	—
15	Combination intervention 9	AMR	SMEI	—	—	—
16	Combination intervention 10	LEI	SMEI	—	—	—
17	Combination intervention 11	HCPP	SI	AMR	—	—
18	Combination intervention 12	HCPP	SI	LEI	—	—
19	Combination intervention 13	HCPP	SI	SMEI	—	—
20	Combination intervention 14	HCPP	AMR	LEI	—	—
21	Combination intervention 15	HCPP	AMR	SMEI	—	—
22	Combination intervention 16	HCPP	LEI	SMEI	—	—
23	Combination intervention 17	SI	AMR	LEI	—	—
24	Combination intervention 18	SI	LEI	SMEI	—	—
25	Combination intervention 19	SI	SMEI	AMR	—	—
26	Combination intervention 20	AMR	LEI	SMEI	—	—
27	Combination intervention 21	HCPP	SI	AMR	LEI	—
28	Combination intervention 22	HCPP	SI	AMR	SMEI	—
29	Combination intervention 23	SI	AMR	LEI	SMEI	—
30	Combination intervention 24	AMR	SMEI	LEI	HCPP	—
31	Combination intervention 25	HCPP	SI	AMR	LEI	SMEI

intervention combination, followed by every three intervention combination, every four intervention combination, and finally the combination of all five interventions. A summary of the scenarios defined is shown in Table 6.2.

Finally, in order to perform scenario testing, the change by which each decision point variable of the respective intervention is altered, must be defined. Each scenario is tested by increasing the decision point variable by an defined low, medium and high percentage so as to determine the causal effects of each scenario on the reduction of diabetic death rate. Although the dynamics of the prediabetic, diabetic and diabetic with complications populations are also observed, primary focus is placed on the diabetic death rate. The effects of the low, medium and high percentage also demonstrate the sensitivity of the developed model to each scenario.

The ranges by which the variable load of each intervention was altered is determined as: 3% – 9% for the *HCPP* intervention, 9% – 40% for both the *SMEI* and *LEI* interventions, 6% – 20% for the *SI* intervention, and 28% – 48% for the *AMR* intervention. The calculations associated with these variable load ranges are shown in Appendix B.

6.1.2 Scenario testing results

Following the development and definition of the scenarios, as discussed in §6.1.1, the baseline of the model (Scenario 1) is always shown so as to determine the effect of each additional scenario on the baseline of the system in scenario testing. For purpose of this research, undiagnosed and diagnosed diabetic deaths per year are used as the baseline measurements for the analysis. Figure 6.1 displays the simulation model results for the system's baseline indicating the behaviour of undiagnosed and diagnosed diabetic deaths per year over the time horizon from 2014–2030. It may seen in Figure 6.1 that 10 720 undiagnosed and 23 670 diagnosed diabetic deaths are observed per year in the year 2030. These values of 10 720 undiagnosed and 23 670 diagnosed diabetic deaths per year are thus used as key indicators in the analysis and evaluation of the scenario testing results.

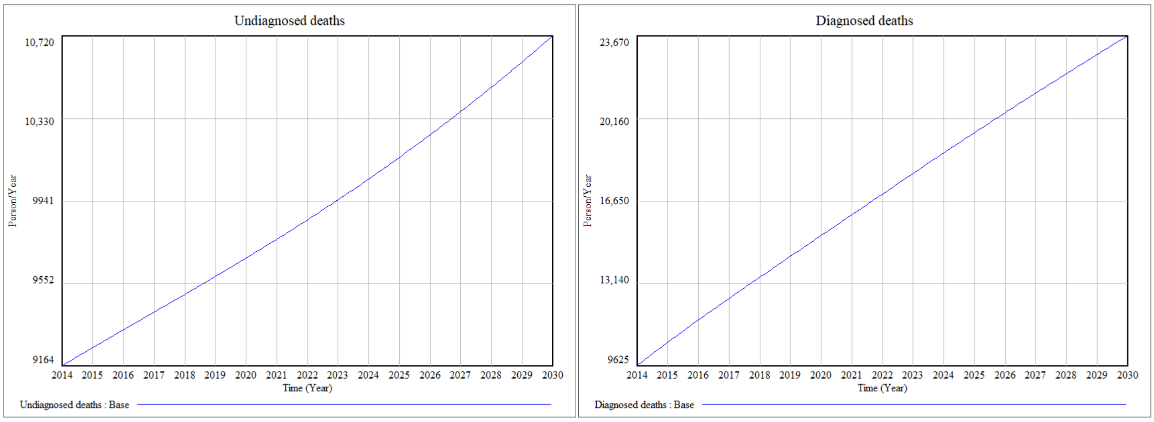


FIGURE 6.1: *System dynamics baseline model results indicating the behaviour of the undiagnosed and diagnosed diabetic deaths per year from 2014–2030.*

As described in §6.1.1, five identified interventions are applied individually in varying combinations which results in thirty scenarios in addition to the first baseline scenario, as shown in Table 6.2. The interventions are then increased at a defined low, medium and high variable load for each scenarios so as to test the effect of each scenario on the undiagnosed and diagnosed diabetic death rates per year. Figures 6.2–6.6 show the system dynamics model simulation results of Scenarios 2–6 (or the five 'base interventions') and the effect of the variable load increases. The remaining system dynamics model simulation results, namely Scenarios 7–31, may be found in Appendix C. The results of the individual scenario tests are presented in Table 6.3.

In order to compare the results presented in Table 6.3, a relationship matrix is developed and shown in Table 6.4. The results of each scenario test (or, more specifically, the results of each variable load increase per scenario test), are compared to the baseline undiagnosed and diagnosed diabetic deaths per year in the form of a percentage improvement on the baseline. As shown in the table, a heat map is used to indicate the best performing scenarios for both the undiagnosed and diagnosed diabetic deaths per year — as the colour of a cell darkens, the respective diabetic deaths per year for the associated scenario significantly reduces.

TABLE 6.3: *Summary of the model simulation scenario testing.*

Scenario number	Scenario name	Interventions applied					Variable load on diabetic deaths per year					
							Undiagnosed			Diagnosed		
							Low	Medium	High	Low	Medium	High
1	Baseline	—	—	—	—	—	Baseline of 10 720 undiagnosed and 23 670 diagnosed diabetic deaths per year					
2	Health care professional to patient ratio intervention	HCPP	—	—	—	—	10 710	10 700	10 690	22 540	21 420	20 320
3	Screening intervention	—	SI	—	—	—	10 640	10 460	10 260	24 370	25 750	27 340
4	Availability of medical resources intervention	—	—	AMR	—	—	10 700	10 680	10 660	22 070	20 540	19 250
5	Lifestyle education intervention	—	—	—	LEI	—	10 710	10 710	10 710	22 600	22 060	21 520
6	Self-management education intervention	—	—	—	—	SMEI	10 720	10 720	10 720	22 970	22 050	20 720
7	Combination intervention 1	HCPP	SI	—	—	—	10 630	10 450	10 250	23 170	23 110	22 960
8	Combination intervention 2	HCPP	—	AMR	—	—	10 690	10 660	10 620	21 020	18 640	16 610
9	Combination intervention 3	HCPP	—	—	LEI	—	10 700	10 690	10 680	21 530	20 010	18 570
10	Combination intervention 4	HCPP	—	—	—	SMEI	10 710	10 700	10 700	21 770	18 820	15 340
11	Combination intervention 5	—	SI	AMR	—	—	10 620	10 430	10 220	22 690	22 160	21 640
12	Combination intervention 6	—	SI	—	LEI	—	10 630	10 450	10 250	23 280	24 060	24 960
13	Combination intervention 7	—	SI	—	—	SMEI	10 640	10 470	10 280	23 620	23 770	23 370
14	Combination intervention 8	—	—	AMR	LEI	—	10 690	10 670	10 650	21 080	19 170	17 570
15	Combination intervention 9	—	—	AMR	—	SMEI	10 700	10 680	10 660	21 410	19 150	16 860
16	Combination intervention 10	—	—	—	LEI	SMEI	10 710	10 710	10 710	21 950	20 670	19 060
17	Combination intervention 11	HCPP	SI	AMR	—	—	10 720	10 610	10 290	21 570	19 910	17 830
18	Combination intervention 12	HCPP	SI	—	LEI	—	10 620	10 440	10 330	22 160	21 640	20 520
19	Combination intervention 13	HCPP	SI	—	—	SMEI	10 630	10 460	10 370	22 350	20 010	16 330
20	Combination intervention 14	HCPP	—	AMR	LEI	—	10 680	10 650	10 610	20 100	17 430	15 230
21	Combination intervention 15	HCPP	—	AMR	—	SMEI	10 690	10 660	10 620	20 300	16 390	12 530
22	Combination intervention 16	HCPP	—	—	LEI	SMEI	10 700	10 690	10 680	20 830	17 730	14 280
23	Combination intervention 17	—	SI	AMR	LEI	—	10 610	10 420	10 270	21 690	20 740	19 820
24	Combination intervention 18	—	SI	—	LEI	SMEI	10 630	10 460	10 210	22 580	22 280	21 460
25	Combination intervention 19	—	SI	AMR	—	SMEI	10 620	10 430	10 240	21 970	20 430	18 350
26	Combination intervention 20	—	—	AMR	LEI	SMEI	10 690	10 670	10 650	20 470	17 970	15 580
27	Combination intervention 21	HCPP	SI	AMR	LEI	—	10 600	10 400	10 190	20 650	18 670	16 660
28	Combination intervention 22	HCPP	SI	AMR	—	SMEI	10 610	10 420	10 220	20 810	17 200	12 950
29	Combination intervention 23	—	SI	AMR	LEI	SMEI	10 610	10 420	10 220	21 030	19 180	16 920
30	Combination intervention 24	HCPP	—	AMR	LEI	SMEI	10 680	10 650	10 610	19 440	15 470	11 730
31	Combination intervention 25	HCPP	SI	AMR	LEI	SMEI	10 600	10 410	10 210	19 930	16 220	12 060

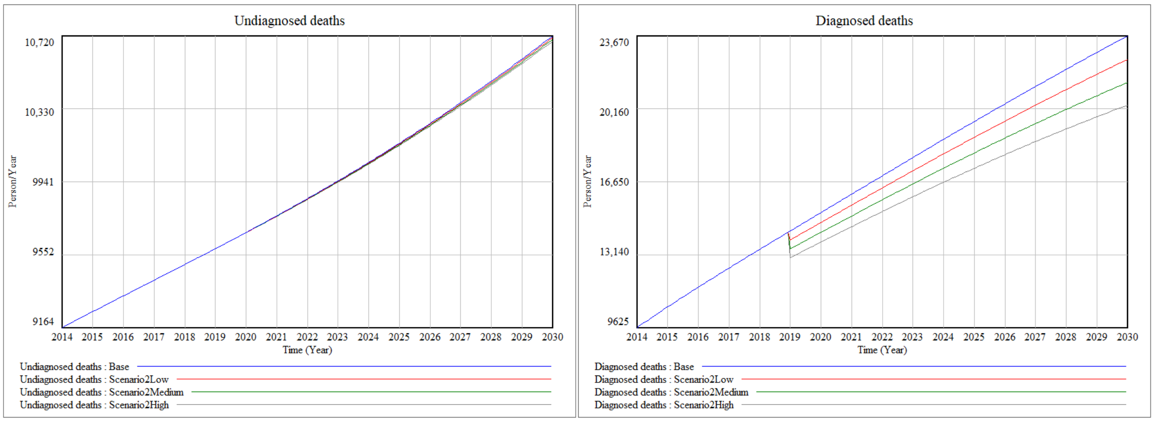


FIGURE 6.2: *System dynamics model results of Scenario 2.*

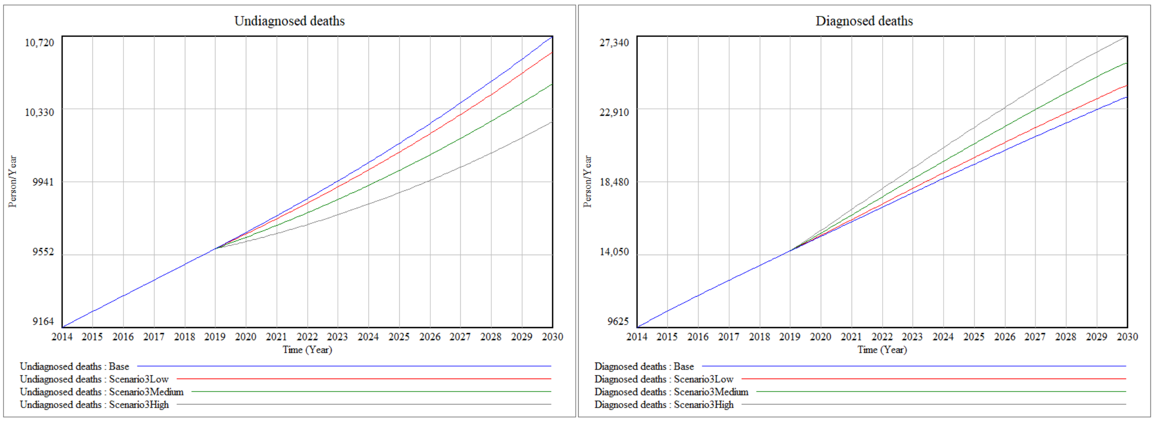


FIGURE 6.3: *System dynamics model results of Scenario 3.*

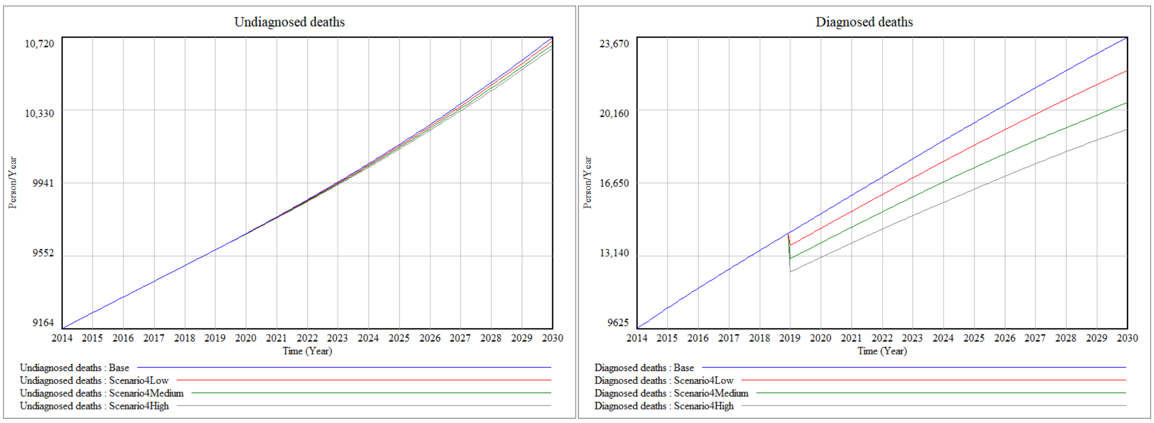


FIGURE 6.4: *System dynamics model results of Scenario 4.*

An initial assessment of Table 6.4 reveals that, while the *SI* intervention alone and in combinations with other interventions appears to reduce the undiagnosed diabetic deaths per year, this intervention leads to less of an overall reduction, and, in some cases, an increase in the diagnosed diabetic deaths per year. As discussed in §5.3.2, the *SI* intervention plays an im-

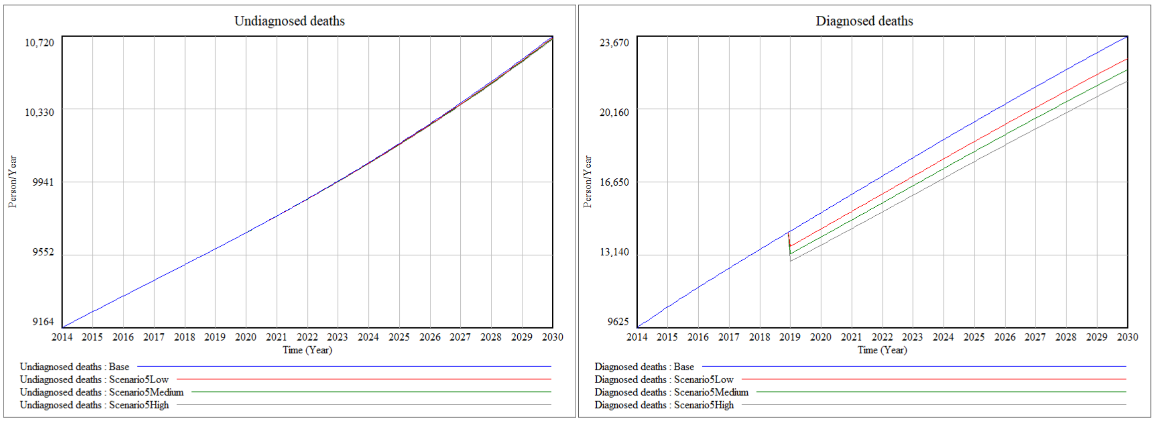


FIGURE 6.5: *System dynamics model results of Scenario 5.*

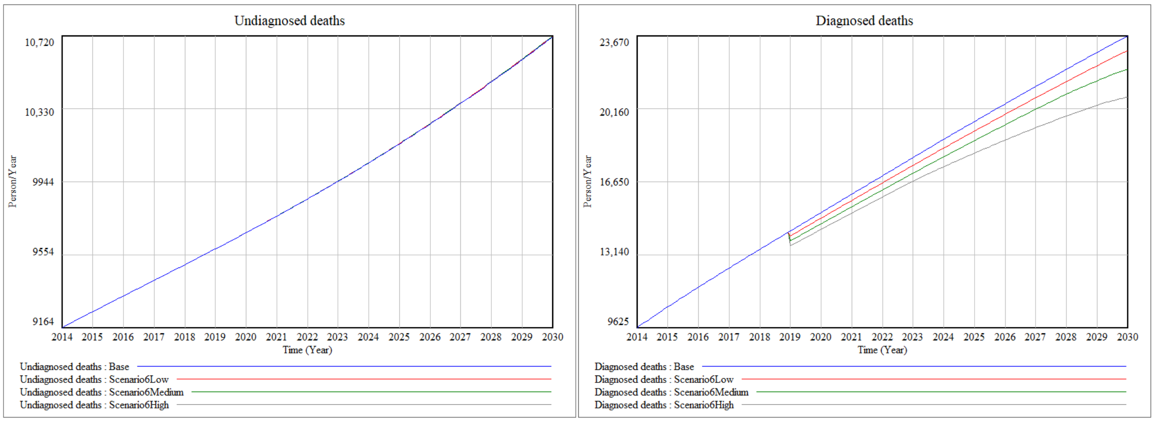


FIGURE 6.6: *System dynamics model results of Scenario 6.*

portant role in the diagnosis of the undiagnosed diabetic population. As expected, when the *SI* intervention is utilised, more of the undiagnosed diabetic population are diagnosed, leading to a decreased undiagnosed population and increase diagnosed population. These changes in diabetic population sizes ultimately influences the undiagnosed and diagnosed diabetic death rates per year. Similarly, it may be seen in Table 6.4 that scenarios involving the *HCPP* and the *AMR* interventions slightly reduce the undiagnosed diabetic deaths per year. As discussed in §5.3.2, these two intervention also play a role in the diagnosis of the undiagnosed diabetic populations. The *HCPP* and the *AMR* interventions do not, however, have a significant impact on the diagnosis of the undiagnosed populations, and, consequently, do not significantly reduce the undiagnosed diabetic deaths per year as much as the *SI* intervention. These two aforementioned interventions, in addition to the *LEI* and *SMEI* interventions, each have a varying impact on the management of the diabetic disease, and, therefore, influence the reduction of the diagnosed diabetic deaths per year.

The outcomes of the aforementioned scenario results illustrates the usefulness of the system dynamics modelling approach to identify and model the effects of causal relationships, especially when considering a complex, dynamic system where non-linear relationships are not generally easy to identify. These scenario results may, therefore, prove useful in providing insight into the diabetic health system in South Africa so as to assist the development of policy strategy and intervention recommendations.

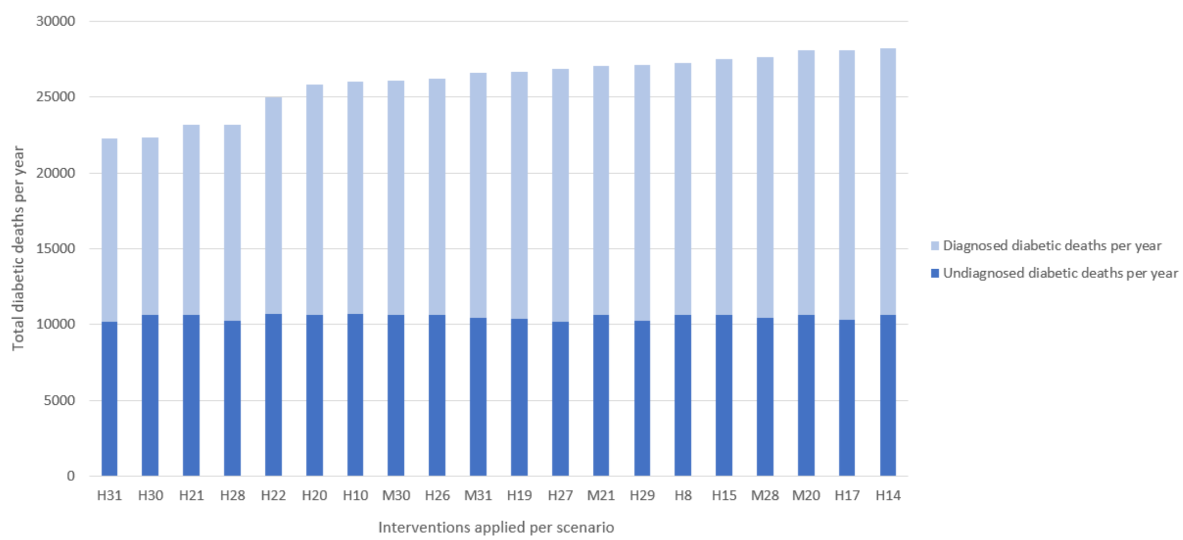
TABLE 6.4: *Relationship matrix on the effect of each variable load increase on each scenario in reducing the diagnosed diabetic death rate per year.*

Scenario number	**Scenario name**	**Interventions applied**					**Variable load on diabetic deaths per year**					
							Undiagnosed			**Diagnosed**		
							Low	**Medium**	**High**	**Low**	**Medium**	**High**
1	Baseline	—	—	—	—	—	Baseline of 10 720 undiagnosed and 23 670 diagnosed diabetic deaths per year					
2	Health care professional to patient ratio intervention	HCPP	—	—	—	—	0.09%	0.19%	0.28%	4.77%	9.51%	14.15%
3	Screening intervention	—	SI	—	—	—	0.75%	2.43%	4.30%	-2.96%	-8.79%	-15.50%
4	Availability of medical resources intervention	—	—	AMR	—	—	0.19%	0.37%	0.56%	6.76%	13.22%	18.67%
5	Lifestyle education intervention	—	—	—	LEI	—	0.09%	0.09%	0.19%	4.52%	6.80%	9.08%
6	Self-management education intervention	—	—	—	—	SMEI	0.00%	0.00%	0.00%	2.96%	6.84%	12.46%
7	Combination intervention 1	HCPP	SI	—	—	—	0.84%	2.52%	4.39%	2.11%	2.37%	3.00%
8	Combination intervention 2	HCPP	—	AMR	—	—	0.28%	0.56%	0.93%	11.20%	21.25%	29.83%
9	Combination intervention 3	HCPP	—	—	LEI	—	0.19%	0.28%	0.37%	9.04%	15.46%	21.55%
10	Combination intervention 4	HCPP	—	—	—	SMEI	0.09%	0.19%	0.19%	8.03%	20.49%	35.19%
11	Combination intervention 5	—	SI	AMR	—	—	0.93%	2.71%	4.67%	4.14%	6.38%	8.58%
12	Combination intervention 6	—	SI	—	LEI	—	0.84%	2.52%	4.39%	1.65%	-1.65%	-5.45%
13	Combination intervention 7	—	SI	—	—	SMEI	0.75%	2.34%	4.11%	0.21%	-0.42%	1.27%
14	Combination intervention 8	—	—	AMR	LEI	—	0.28%	0.47%	0.65%	10.94%	19.01%	25.77%
15	Combination intervention 9	—	—	AMR	—	SMEI	0.19%	0.37%	0.56%	9.55%	19.10%	28.77%
16	Combination intervention 10	—	—	—	LEI	SMEI	0.09%	0.09%	0.09%	7.27%	12.67%	19.48%
17	Combination intervention 11	HCPP	SI	AMR	—	—	0.00%	1.03%	4.02%	8.87%	15.89%	24.67%
18	Combination intervention 12	HCPP	SI	—	LEI	—	0.93%	2.62%	3.64%	6.38%	8.58%	13.31%
19	Combination intervention 13	HCPP	SI	—	—	SMEI	0.84%	2.43%	3.27%	5.58%	15.46%	31.01%
20	Combination intervention 14	HCPP	—	AMR	LEI	—	0.37%	0.65%	1.03%	15.08%	26.36%	35.66%
21	Combination intervention 15	HCPP	—	AMR	—	SMEI	0.28%	0.56%	0.93%	14.24%	30.76%	47.06%
22	Combination intervention 16	HCPP	—	—	LEI	SMEI	0.19%	0.28%	0.37%	12.00%	25.10%	39.67%
23	Combination intervention 17	—	SI	AMR	LEI	—	1.03%	2.80%	4.21%	8.37%	12.38%	16.27%
24	Combination intervention 18	—	SI	—	LEI	SMEI	0.84%	2.43%	4.77%	4.60%	5.87%	9.34%
25	Combination intervention 19	—	SI	AMR	—	SMEI	0.93%	2.71%	4.49%	7.18%	13.69%	22.48%
26	Combination intervention 20	—	—	AMR	LEI	SMEI	0.28%	0.47%	0.65%	13.52%	24.08%	34.18%
27	Combination intervention 21	HCPP	SI	AMR	LEI	—	1.12%	2.99%	4.95%	12.76%	21.12%	29.62%
28	Combination intervention 22	HCPP	SI	AMR	—	SMEI	1.03%	2.80%	4.67%	12.08%	27.33%	45.29%
29	Combination intervention 23	—	SI	AMR	LEI	SMEI	1.03%	2.80%	4.67%	11.15%	18.97%	28.52%
30	Combination intervention 24	HCPP	—	AMR	LEI	SMEI	0.37%	0.65%	1.03%	17.87%	34.64%	50.44%
31	Combination intervention 25	HCPP	SI	AMR	LEI	SMEI	1.12%	2.90%	4.77%	15.80%	31.47%	49.05%

6.2 Scenario analysis

Following the scenario testing results presented in §6.1.2, promising or notable scenarios may now be considered for analysis.

When considering a single-objective problem, where the aim is to minimise the total diabetic deaths per year, a solution space may be presented in the form of a stacked bar graph, consisting of both the undiagnosed and diagnosed diabetic deaths per year, as shown in Figure 6.7. This bar graph displays the twenty scenarios which achieved the lowest total diabetic death rate per year in 2030, as well as the interventions applied for every scenario, where the letters 'H', 'M' and 'L' indicates a high, medium and low variable loads, respectively, for each specific numbered scenario.



HCPP	HCPP	HCPP	HCPP	HCPP	HCPP	HCPP	HCPP	-	HCPP	HCPP	HCPP	HCPP	---	HCPP	-	HCPP	HCPP	HCPP	-
SI	-	-	SI	-	-	-	-	-	SI	SI	SI	-	SI	-	-	SI	-	SI	-
AMR	AMR	AMR	AMR	-	AMR	-	AMR	AMR	AMR	-	AMR	AMR	AMR	AMR	AMR	AMR	AMR	AMR	AMR
LEI	LEI	-	-	LEI	LEI	-	LEI	LEI	LEI	-	LEI	-	LEI	-	-	-	LEI	-	LEI
SMEI	SMEI	SMEI	SMEI	SMEI	-	SMEI	SMEI	SMEI	SMEI	SMEI	-	SMEI	SMEI	-	SMEI	SMEI	-	-	-

FIGURE 6.7: *The twenty scenarios with the lowest total diabetic death rates per year in 2030.*

As may be seen in Figure 6.7, scenario H31 performs the best overall in decreasing the total diabetic deaths per year, which is expected since it considers the implementation of all five interventions at a high variable load. Scenario H30 performs the second best in reducing the total diabetic deaths per year by utilising all the interventions except the *SI* intervention. The impact of the combination of interventions for Scenario H30 is realised by observing that Scenario M30, which employs the same interventions as H30 but at a medium variable load, is the eighth best performing scenario, outperforming the majority of scenarios with a high variable load. Scenario M30 also outperforms Scenario M31 — a different observation at a medium variable load. Another interesting observation is Scenario H21 (a three-intervention scenario) which outperforms most of the four-intervention scenarios. Scenario H21 may be seen as a combination of Scenarios H22 and H20 (with the exclusion of the *LEI* intervention), where these scenarios perform the fifth and sixth best, respectively, in reducing the total diabetic deaths per year in 2030. A similar scenario to Scenario H21 is Scenario H10 (a two-intervention scenario), which outperforms almost all of the three-intervention scenarios making it the seventh best overall performing scenario, while Scenario H8, the next nearest two-intervention scenario, only ranks fifteenth best.

If this problem was instead considered from a bi-objective perspective, where the aim is to minimise both the undiagnosed and diagnosed diabetic deaths per year, a solution space may then be presented in the form of a scatter plot, as shown in Figure 6.8. This scatter plot displays the relationship between the undiagnosed and diagnosed diabetic deaths per year of each variable load of each scenario, where again the letters 'H', 'M' and 'L' indicates a high, medium and low variable load, respectively, for each specific numbered scenario.

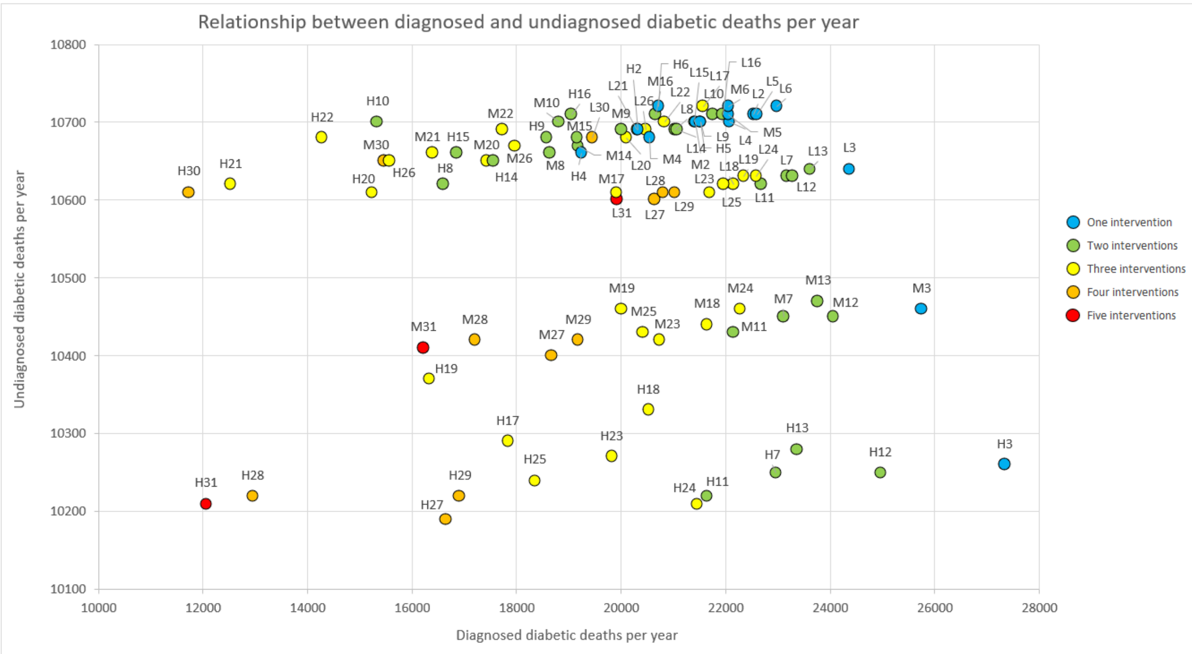


FIGURE 6.8: *Relationship between diagnosed and undiagnosed diabetic deaths per year in 2030.*

An initial observation of the scatter plot in Figure 6.8 shows that scenarios with more interventions at a high variable load generally perform better in minimising both the undiagnosed and diagnosed diabetic deaths per year. In this bi-objective problem solution space, a Pareto set[1] of non-dominated solutions emerges — Scenarios H30, H31 and H27. These scenarios may also be found in the top twelve best performing scenarios in Figure 6.7, with H31 and H30 performing the first and second best, respectively, in reducing the total diabetic deaths per year. Other points for consideration, due to their close proximity to the Pareto set, include Scenarios H28 and H29 (each implementing four interventions) as well as Scenarios H21 (a three-intervention scenario). Although performing poorly in reducing the undiagnosed diabetic deaths per year, Scenarios H20 and H22 (each implementing three interventions) are shown to perform well in reducing the diagnosed diabetic deaths per year. These results may now be analysed so as to determine effective intervention combinations, as well as the effects of causal relationships of various interventions on the diabetic health care system.

A promising intervention combination is in the form of Scenario H10, where both the *HCPP* and *SMEI* interventions are implemented at a high variable load. Although not initially identified

[1]Pareto optimisation is an area of multiple objective decision-making which considers mathematical optimisation problems, involving more than one objective function to be optimised, simultaneously [13, 78]. The Pareto front is the set of all Pareto efficient allocations or non-dominated solutions [13].

using Figure 6.8, this two-intervention scenario proves to be an effective intervention combination since it largely outperforms the majority of the three- and four-intervention scenarios. When the *HCPP* intervention of this scenario is considered, it is important to note how crucial well-trained and dedicated health care professionals are in the organisation of diabetic care, as discussed in §2.1.5 — from the diagnosis of the disease to the management of diagnosed diabetes. A sufficient number of health care professionals ensure that the diabetic treatment procedure is followed in initial and follow up consultations, therefore, ensuring that undiagnosed diabetics are diagnosed, or that diagnosed diabetes is managed according to the treatment procedure in diabetic policy. It is, therefore, unsurprising that, as the health care professional to patient ratio (*i.e.* the *HCPP* intervention) is increased, the total diabetic deaths per year are reduced, as shown in the scenario. As further discussed in §2.1.5, diabetic self-management education, the second intervention of scenario H10, is a vital component in the organisation of diabetic care and leads to the successful individual management of the diabetes disease. Diabetic self-management education must, however, be presented by health care professionals. Since the self-management education (*i.e.* the *SMEI* intervention), which was already shown to manage the diabetes disease effectively in §2.1.5, is driven by the availability of health care professionals to administer the intervention, increasing the availability of health care professionals not only leads to more diabetic diagnoses and improved adherence to the treatment procedure in consultations, but also to more health care professionals being available to present self-management education to diabetics. Logical argumentation therefore aligns the finding that increasing the combination of the *SMEI* and *HCPP* interventions would lead to a significantly greater adherence to the treatment procedure required in diabetic consultations and a larger availability of health care professionals to present self-management education. This leads to better management of the diabetes disease and reduces the total diabetic deaths per year, as confirmed in Scenario H10.

Although only performing fifteenth best in reducing the total diabetic deaths per years, another notable intervention combination is found in Scenario H8, the second best performing two-intervention scenario, which outperforms approximately half of the three-intervention scenarios. This scenario consists of both the *HCPP* and *AMR* interventions. As previously explained for the *HCPP* intervention, by increasing the availability of health care professionals, there is greater adherence to the diabetic treatment procedure, which leads to more diabetic diagnoses and improved management of the diabetic disease. As discussed in §2.1.5, functioning equipment, as well as a regular and sustainable supply of medication, play an important role in adhering to the diabetic treatment procedure by ensuring that the disease is treated with the correct pharmaceuticals and that equipment required to conduct disease diagnostics is available. By increasing the *AMR* intervention, the diabetic treatment procedure can be better maintained, leading to the improved management of diagnosed diabetics, which results in a reduced diagnosed diabetic rate per year. As discussed in 5.3.2, both the availability of medical resources and the health care professional to patient ratio influence the adherence of the diabetic treatment procedure outlined in policy. This complementary relationship of the *HCPP* and *AMR* interventions in Scenario H8, therefore, leads to the improved adherence to the diabetic treatment procedure in consultations and results in a reduction in the total number of diabetic deaths per year.

The relationship between the *HCPP-SMEI* and *HCPP-AMR* intervention combinations are further illustrated in Scenarios H22 and H20, respectively. With the addition of the *LEI* intervention to each scenario, the combination of the *HCPP* and *SMEI* interventions improves from the seventh to the fifth best performing scenario in reducing the diabetic death rates, while the combination of the *HCPP* and *AMR* interventions improves from the fifteenth to the sixth best performing scenario. There is perhaps no direct relationship with the combinations of interventions with the *LEI* intervention, but the lifestyle education intervention has proven to be an effective supportive intervention to the already powerful intervention combinations.

Arguably, the most powerful intervention combination is observed in all four of the best performing scenarios in reducing the total diabetic deaths per year. This combination includes the *HCPP*, *SMEI* and *AMR* interventions, and is also the best performing three-intervention combination, as well as the third best performing scenario overall. The impact of interventions *HCPP*, *SMEI* and *AMR* may be observed in Figure 6.7, where a significant drop is observed in the total diabetic death rate per year between Scenarios H28 and H22. In Scenario 28, as well as in the remaining best performing scenarios (*i.e.* Scenarios H21, H30 and H31), the combination of interventions *HCPP*, *SMEI* and *AMR* is present and likely accounts for the significant decrease in the total diabetic death rate per year. This combination of interventions is also observed in Scenarios M21, M28, M30 and M31 in Figure 6.7. It is perhaps surprising that a combination of interventions at a medium variable load are able to outperform interventions at a high variable load. This further illustrates the powerful combination of the *HCPP*, *SMEI* and *AMR* interventions — even at a medium load, these scenarios are able to outperform two thirds of high variable load scenarios. A strong causal relationship may, therefore, be observed between the health care professional to patient ratio, self-management education and availability of medical resources interventions.

With interventions *HCPP*, *SMEI* and *AMR* identified as a powerful intervention combination, the effect of including the *LEI* intervention may be demonstrated once more. Scenario 21 consists of *HCPP*, *SMEI* and *AMR* interventions as well as the *LEI* intervention. It can be seen in Figure 6.7 that Scenario H30 results in a greater decrease in the total diabetic deaths per year when compared to Scenario H21 (which does not include the *LEI* intervention). It is again evident that the *LEI* intervention is an effective supportive intervention to an already powerful intervention combination.

The final scenarios considered in this analysis are the first and second best performing intervention combinations (*i.e.* Scenarios H31 and H30, respectively). Scenario H31 comprises all five base interventions at a high variable load and outperforms every other scenario. This is justifiable since one would expect that the most significant reduction in total diabetic deaths would be realised through the application of all interventions at a high variable load. This result, therefore, acts as a further verification of the build and structure of the system dynamics model. Scenario H30, the best performing four-intervention combination, comprises the *HCPP*, *SMEI*, *LEI*, and *AMR* interventions and excludes the *SI* intervention. As discussed in §6.1.2, when the *SI* intervention is utilised, more of the undiagnosed diabetic population are diagnosed, leading to a decrease in the undiagnosed population and increase in the diagnosed population. These changes in diabetic population sizes ultimately influences the undiagnosed and diagnosed diabetic death rates per year. Similarly, scenarios involving the *HCPP* and *AMR* interventions also appear to slightly reduce the undiagnosed diabetic deaths per year, since these two intervention also play a role in diagnosis of the undiagnosed diabetic populations. The *HCPP* and the *AMR* interventions do not, however, have a significant impact on the diagnosis of the undiagnosed populations, and, consequently, do not significantly reduce the undiagnosed diabetic deaths per year as much as the *SI* intervention. The *HCPP* and *AMR* interventions, in combination with the *LEI* and *SMEI* interventions, each have a varying impact on the management of the diabetic disease, and, therefore, influence the reduction of the diagnosed diabetic deaths per year. Although the screening intervention was observed to be the most appropriate intervention in reducing the total undiagnosed diabetic deaths per year, the impact of the screening intervention on the undiagnosed diabetic deaths per year was significantly less than the impact of the other four interventions on the diagnosed diabetic deaths per year, as illustrated in Scenario H30.

When considering research objective VII in §1.4, which consists of recommending policy strategy and intervention recommendations for the management of diabetes in South Africa, the level or type of policy strategy and intervention recommendations must be defined. As stated in the research scope in §1.5, this research does not focus on the acquisition of detailed data relating to the South African health care system, the availability of human and medical resources, and various diabetes-related interventions and measures, since these data are largely unavailable in South Africa or not open to the public. Instead, the aim of this research was the development of a system dynamics model so as to accurately identify and depict the various causal relationships between stakeholders, resources and patients found within the diabetic health care system in South Africa. Since the data used in the system dynamics model are largely based on estimates and assumptions, it would, therefore, not be appropriate to formulate detailed policy strategy and intervention recommendations based on the results of the scenario testing. The system dynamics model does, however, provide insight into the complexity and dynamic nature of the diabetic health care system in South Africa, together with a better understanding of the non-linear relationships between various elements in the system. The results of the scenario testing may, therefore, be appropriately used to form high-level policy considerations to address the management of the diabetes disease in South Africa.

6.3 Policy conclusions

With the preceding discussions in mind, the policy considerations presented in this section aim to provide insight into the complex and dynamic diabetic health care system, as well as to highlight effective causal relationships.

When only implementing two interventions, powerful causal relationships are observed between the health care professional to patient ratio and self-management education interventions, as well as between the health care professional to patient ratio and the availability of medical resources interventions. The most significant causal relationship is, however, a union of the aforementioned interventions — the health care professional to patient ratio, self-management education and availability of medical resources interventions. This combination of interventions, alone or including other interventions, was shown to consistently and more significantly reduce the total diabetic deaths than any other intervention combination.

Although the lifestyle education intervention was shown to reduce the total diabetic deaths per year, no strong relationship was identified in combination with other interventions. The lifestyle education intervention, however, proves to be an effective supportive intervention to already powerful intervention combinations. Finally, although the screening intervention was shown to be the most appropriate intervention in reducing the undiagnosed diabetic deaths per year, the impact of the screening intervention on the undiagnosed diabetic deaths per year was significantly less than the impact of the other interventions on the diagnosed diabetic deaths per year.

6.4 Chapter 6 conclusion

As discussed at the onset of Chapter 5, the aim of Part II of this research was to use the system dynamics modelling approach to develop a system dynamics model so as to investigate the effects of intervention strategies on the management of diabetes in South Africa. Following the development of the system dynamics model in Chapter 5, Chapter 6 served to achieve the aforementioned aim of Part II of this research by using the system dynamics model to investigate the policy intervention strategies through scenario testing and analysis so as to develop policy considerations. At the onset of Chapter 6, the policy intervention scenarios were first defined, followed by the scenario testing results of the system dynamics model, in fulfilment of Research Objective VI. Finally, the analysis of the scenario results were used to develop policy considerations so as to address the management of the diabetes disease in South Africa, in fulfilment of Research Objective VII.

Part III

Conclusion

CHAPTER 7

Conclusion and recommendations

Contents

This chapter comprises four sections. In §7.1, a chapter-by-chapter overview of the research documented is provided, together with how the eight research objectives presented in §1.4 were achieved. This is followed in §7.2 by an appraisal of the contributions made in this thesis followed in §7.3 by the limitations of the research. Finally, suggestions for future work are discussed in §7.4.

7.1 Research summary

Apart from this concluding chapter, this research comprised a further six chapters. Chapter 1 contained an introduction to the research by providing a short background of the history of the diabetes mellitus disease, as well its prevalence in the modern world. This was followed in §1.2 by the identified problem statement which the research aimed to address, as well as the research aim, objectives and research scope in §1.3, §1.4, and §1.5, respectively. Finally, the research methodology, as well as the organisational outlay of the research, were discussed in §1.6 and §1.7, respectively.

The thesis content then commenced with a literature study in Chapters 2, 3, and 4. The literature reviewed in Chapter 2 pertained to the diabetes mellitus disease in South Africa. An analysis of the diabetes disease was provided at the onset of Chapter 2. Thereafter, the disease was classified according to its clinical stages and aetiological features in §2.1.2. The diagnosis and screening of diabetes was then discussed in §2.1.3 and §2.1.4, respectively. Finally, the section concluded with the organisation of diabetic care in §2.1.5 and diabetic complications in §2.1.6. An analysis of the South African health care system was then presented in §2.2, wherein the efficiency of the system, as well as the inequality between the public and private health care system and the increased burden of disease, were discussed in §2.2.1, §2.2.2 and

§2.2.3, respectively. The growing prevalence of diabetes in South Africa was then highlighted. As discussed in §2.3.1, it is estimated that approximately 7% of South Africans between the ages of 21–79 years, or 3.91 million individuals, have diabetes. Furthermore, it was indicated that, of the 3.91 million people living with diabetes, 2.38 million (or 61.1%) are undiagnosed. Thereafter, a discussion of the economic implications followed in §2.3.2. In §2.2.3, the management of the diabetes disease within South Africa was analysed, together with the need to address diabetes by employing diabetic management intervention strategies. Furthermore, the 2017 SEMDSA *Guidelines for the management of type 2 diabetes mellitus diabetic guideline* and the 2017 South African DOH *Management of type 2 diabetes in adults at primary care level* policy were noted as prominent elements for the management of diabetic care in South Africa. The focus of the chapter then shifted to determining the level analysis of the study in §2.4 through the use of a hierarchical perspective. It was shown that health care policy on the meso-level plays a significant role in the management of the diabetes disease in South Africa. Furthermore, as the elements in the macro- and micro-level have such a significant effect on the health care policy in the meso-level, it was further suggested that the entire South African health care system should be considered as the level of analysis for this research (from both a macroscopic and microscopic perspective). The need to investigate the policy domain for the effective management of diabetes in South Africa was evident from the information presented in this chapter.

The literature review in Chapter 3 pertained to diabetic policy and intervention strategies in South Africa. At the onset of this chapter in §3.1, the concept of policy was defined within both a public and health care paradigm. This section further built on the concepts of *public policy* and *private policy*, as well as illustrating how policy is supported by South African legislation. Finally, the definition of *public health care policy* was expanded upon and further defined. Various policy analysis methods were then presented and discussed in §3.2. These policy analysis methods include the policy analysis triangle, the effect-implementation approach to policy analysis and advanced policy methods, such as modelling approaches. The focus of the chapter then shifted in §3.3 to global diabetic responses. The WHO was identified in §3.3.1 as the most prominent health care body to address the management of diabetes on a global scale through policy. Alternative intervention strategies which were shown to have successfully managed other NCDs were then investigated in §3.3.2. Lung, colon, prostate and breast cancer were reports as being the only NCDs decreasing in mortality rate, which is largely attributed to early diagnosis through screening and more targeted education to high-risk individuals. A systematic review of international diabetic policies was then presented in §3.4. The section began by introducing the methodology of a systematic review in §3.4.1. Thereafter, in §3.4.2, public diabetic policies from Australia, Canada, Denmark, Ireland, Malta, Marshall Islands, South Africa and the United Kingdom, as well as private diabetic polices from South Africa and the USA, were selected for review, followed by the details obtained in the WHO diabetic profile for each country. The systematic review of the international polices in §3.4.3 was then presented in Table 3.3. It was found that a weak relationship existed between the content addressed in a diabetic policy and the diabetic prevalence of a country. Since the South African diabetic policy met the highest number of criterion in terms of content addressed in the policy, it was, therefore, determined that further improving the content of the diabetic policy would not act as a suitable intervention strategy to more effectively management diabetes in South Africa. It was then suggested that a more detailed policy analysis should be conducted on South African diabetic policy. Finally, a diabetes register, implemented by Denmark and Ireland, showed success in reducing the diabetes mortality rate in both countries, and was, therefore, identified as a possible intervention strategy for the management of diabetes in South Africa. The chapter concluded in §3.5 with an analysis of South African diabetic policy using the policy triangle method. The policy analysis determined that significant focus is often placed on the content of a policy, and that the context, process and actors were largely omitted in the policy making-process. It was determined that there exists a need to investigate existing intervention strategies for the management of diabetes in South Africa thereby fulfilling Research Objective I. As the policy analysis triangle is, however, limited in determining only a high-level overview of the policy during analysis, it was recommended that, in order to obtain a more detailed and dynamic understanding of the South African diabetic policies, it may be appropriate to make use of an advanced policy analysis approach which employs modelling.

The literature review in Chapter 4 pertained to alternative modelling approaches. Following the conclusion of Chapter 3, Chapter 4 began with the objective of identifying an appropriate modelling approach which is capable of modelling the dynamics of diabetic health care in South Africa with the purpose of investigating existing intervention strategies for the management of diabetes. A set of requirement specifications were then developed, in fulfilment of Research Objective II, for the purpose of evaluating various modelling approaches in order to identify the most appropriate approach for this research. The concept of modelling was then presented in §4.2 as a solution to solving problems in the real world. Analytical modelling approaches were then introduced as a method to solving linear and time-independent issues. Some analytical modelling approaches are, however, unable to model complex, dynamic systems that present multiple non-linear interactions. The concept of simulation modelling was then introduced as an approach capable of modelling dynamic, complex systems, and was identified as the most appropriate category of modelling approaches for this research. Thereafter, the most notable simulation modelling approaches, namely system dynamics, discrete-event, and agent-based, were presented and discussed in §4.2.1, 4.2.2, and 4.2.3, respectively. Finally, the set of requirement specifications were used to evaluate the aforementioned modelling approaches. Discrete-event modelling was initially eliminated as an appropriate modelling approach due to the typical high amount of low-level details needed to build a discrete-event model, which stood in contrast to the high-level and holistic perspective characteristic of the health care system and diabetic population in South Africa. Agent-based modelling was then also eliminated as an appropriate modelling methodology, due to the bottom-up approach needed to model the system which would not be appropriate when modelling the health care system and diabetic population in South Africa. System dynamics, however, appeared to be the most appropriate approach due to the ability of the approach to model the system from a top-down perspective, and incorporate non-linear, dynamic interactions, as well as adapting well to varied input data and changes to interrelations, and having the capabilities to provide the expected outcome of the system over a time period specified in order to model future predictions. System dynamics modelling was, therefore, identified and selected as the most appropriate approach to model the dynamics of diabetic health care in South Africa, in fulfilment of Research Objective III.

The system dynamics modelling approach was then presented and discussed in detail. First, system dynamics was introduced as a method for analysing complex systems and problems to assess the ability of a system to adjust to change, as well as test various diabetic intervention strategies. Several alternative system dynamics modelling processes were then identified in §4.4.1, for the purpose of this research, however, Sterman's approach was selected. Although the majority of system dynamics approaches follow similar principles, the Sterman approach has five distinct steps including problem articulation, dynamic hypothesis, formulation, testing, and policy formulation and evaluation. The system dynamics tools to be used within the modelling approach were then discussed in §4.4.2, and the mathematical representation of stock and flows described in §4.4.3. Finally, a system dynamics verification and validation strategy was discussed as part of the system dynamics method in §4.4.4.

Chapter 5 contained the system dynamics modelling approach pursued in this research. Problem structuring on a more technical level was discussed in §5.1 so as to identify the problem area under consideration for the investigation of diabetic health care in South Africa. The problem context was first discussed in §5.1.1, where the prevention and treatment of diabetes was identified as a significantly complex and dynamics process. In order to consider the impact of alternative intervention strategies for the management of diabetes in South Africa, key areas or indicators were first identified. The boundary of the model was then presented in §5.1.2. The time horizon was set to run from 2014, which was the year of the implementation of the *Management of type 2 diabetes in adults at primary care level* policy, until 2030, which was in-line with the United Nations' SDGs. Two significant disease-specific boundaries were then defined. The first being that only the type 2 diabetes disease would be considered in this research, due to the disease affecting 95% of all those with diabetes. Secondly, only fatal diabetic complications were considered when modelling the dynamics of diabetics with complications. Finally, preliminary information and data was discussed in §5.1.3. In this section, previous studies relating to the system dynamics modelling of the diabetes were also identified, namely the research of Thomas [114, 116] acted as the basis for this research.

The dynamic hypothesis of the diabetic health care in South Africa was then presented in §5.2. First, the key variables of the diabetic health care system were developed in §5.2.1 using a hierarchical analysis in §2.4.2 and the key areas or indicators identified in §5.1.1. The key variables were then categorised according to the hierarchical perspective so as to determine the causal effect and level of influence of each key variable. In §5.2.2, a dynamic hypothesis was then developed in the form of a twelve-feedback loop CLD so as to demonstrate the causal effect of each variable in the system, as well as to hypothesis the overall behaviour of the diabetic health care system. A stock and flow model was then developed in §5.3 using the *Vensim DSS* software so as to investigate the dynamics of diabetic health care in South Africa, in fulfilment of Research Objective IV. The overview of the stock and flow model structure was first discussed in §5.3.1. In this model overview, the population of stocks and flows portrayed the movement of people entering and exiting the following stages: (i) Normal blood glucose level, (ii) prediabetes, (iii) diabetes, and (iv) diabetes with complications. The prediabetes, diabetes and diabetes with complications stages were further subdivided into stocks of people whose conditions were either diagnosed or undiagnosed. Beyond the population stocks, modifiable factors in the model, which would affect the rates of population flow and may be directly amenable to policy intervention, were then identified. Thereafter, the population of stocks and flows, as well as the mathematical representation of their equations, were described in detail. The initial values, parameters and constants used in the stock and flow model were then presented and reasoned in §5.3.3. The focus then shifted to a discussion and reasoning of the assumptions of the non-linear relationships used within the stock and flow model. These assumptions were related to non-linear relationships assumed within the variables using lookup tables. Finally, the decision variables for points of intervention were identified in §5.3.5. These decision variables were vital for the testing of intervention strategies and scenarios in the system dynamics model. The modelling setting utilised in the *Vensim DSS* system dynamics model was described in §5.3.6, which specified the model simulated time horizon between 2014–2030.

The system dynamics model was then verified and validated in §5.4 according to a system dynamics verification and validation strategy so as to establish the validity of the model, as well as to deem the model outputs to be accurate and credible, in fulfilment of Research Objective V. The system dynamics model was first iteratively verified in §5.4 throughout the process of model development using the verification method defined by Pruyt [89]. After model completion, verification was deemed valid by passing all twelve requirements proposed by Lai and Wahba's "Model Correctness Checklist" [60]. Tests for the model's validity were then conducted. The validation tests and methods used were developed by Forrester and Senge, as described by Sterman, with the model results and tests presented in Appendix A.

Chapter 6 contained the system dynamics model results. First, scenarios were developed in §6.1.1 to test alternative intervention strategies in the system dynamics model so as to determine the strategies most effective in managing diabetic health care in South Africa, in fulfilment of Research Objective VI. The section begin by first identifying the five key decision points in the system dynamics model, which were then translated into five intervention strategies. A baseline scenario was first identified in the case where no interventions were applied, and consisted of both the undiagnosed and diagnosed diabetic deaths per year. Combinations of interventions were then identified as scenarios for scenario testing and were presented in Table 6.2. Finally, in order to perform scenario testing, the variance by which each decision point variable of the respective intervention is altered was defined. It was determined that each scenario was to increase the decision point variable of the specific interventions by a defined low, medium and high percentage to determine the causal effects of each scenario on the reduction of diabetic death rate. The variable load ranges were determined for each intervention. The scenario testing was then conducted and presented in §6.1.2, thereby further fulfilling Research Objective VI. A relationship matrix was also developed and shown in Table 6.4 so as to demonstrate the percentage variance of variable load increase per scenario test to the baseline undiagnosed and diagnosed diabetic deaths per year. With the outcomes of the various scenarios shown to vary based on the impact of each intervention on the diabetic death rate, the results of the scenario testing proved the usefulness of the system dynamics method for identifying and modelling the effects of causal relationships, especially in a complex, dynamic system where non-linear relationships are not generally easy to identify.

The scenario testing results of §6.1.2 were first presented in various solution spaces so as to identify promising scenarios for analysis. The first solution space presentation included a viewpoint of a single-objective problem, where the aim was to minimise the total diabetic deaths year. From this perspective, notable scenarios included two-intervention combinations (Scenarios H8 and H10), three-intervention combinations (Scenarios H20, H21 and H22), and four-intervention combination (Scenario H30) — all of which largely consisted of varying combinations of the *HCPP*, *SMEI* and *AMR* interventions. The scenario results were then presented in the solution space viewpoint of a bi-objective problem, where the aim was to minimise both the undiagnosed and diagnosed diabetic deaths per year. A Pareto set of non-dominated solutions emerged from the scatter plot, namely Scenarios H27, H30 and H31. Scenarios H21, H28 and H29 were also noted due to their proximity to the Pareto set. Following the identification of notable scenarios, these scenarios, as well as the interventions applied for the specific scenario, were discussed in §6.1 so as to determine the aspects of the scenario that impacted the undiagnosed and diagnosed diabetic deaths per year. Strong intervention combinations were identified between the *HCPP* and *SMEI*, and *HCPP* and *AMR* interventions. The most significant combination and relationship was, however, observed between the *HCPP*, *SMEI* and *AMR* intervention combination. Finally, high-level policy considerations were presented in §6.3 so as to address the management of the diabetes disease in South Africa, in fulfilment of Research Objective VII. Policy considerations included the insight of the strong relationships observed in the two-intervention combination of the health care professional to patient ratio and self-management education interventions, as well as the health care professional to patient ratio and availability of medical resources interventions, in reducing the total diabetic deaths per year. The most significant relationship which was observed was the combination of the aforementioned three interventions. Although the lifestyle education intervention was shown to reduce the total diabetic deaths per year, no strong relationship was identified with other interventions. The lifestyle education intervention, therefore, proved to be an effective supportive intervention to already powerful combination interventions. Finally, although the screening intervention was shown to be the most appropriate intervention in reducing the undiagnosed diabetic deaths per year, the impact of the screening intervention on the undiagnosed diabetic deaths per year was significantly less than the impact of the other interventions on the diagnosed diabetic deaths per year.

7.2 Appraisal of research contributions

The contributions of this research are three-fold and are listed in this section in the order by which they appear throughout this research.

Contribution 1 *Determining the need to investigate existing intervention strategies for the management of diabetes in South Africa, as well as identifying an appropriate method for investigation.*

Following the analysis in Chapter 2, it was determined that existing policy and intervention strategies should be investigated to manage diabetes in South Africa. After conducting a policy analysis in Chapter 3, it was determined that it may be appropriate to make use of a more advanced policy analysis approach, such as a modelling, to obtain a more detailed and dynamic understanding of South African diabetic policies. An analysis and evaluation of alternative modelling methods in Chapter 4 led to the identification of system dynamics as an appropriate method for investigate existing strategies for diabetic policy formulation in South Africa.

This aforementioned argument was presented in the article titled "*Considering the need for alternative intervention strategies for the management of diabetes in South Africa*" at the 29$^{\text{th}}$ annual *South African Institute of Industrial Engineering* (SAIIE) conference in Stellenbosch, South Africa, and consequently published in the 29$^{\text{th}}$ annual SAIIE conference proceedings [114]. The full article citation is as follows: Thomas V, de Kock I & Bam L. (2018). "Considering the need for alternative intervention strategies for the management of diabetic policy formulation in South Africa." Proceedings of the *SAIIE29 Conference, 24th–26th of October 2018, Spier, Stellenbosch, South Africa*, pp. 295–306. This article may be viewed in Appendix D.1.

Contribution 2 *The design and implementation of a system dynamics model that correctly models the causal relationships and dynamics of the diabetic health care system, as well as the diabetes populations, in South Africa.*

In Chapter 5, a system dynamics model was developed in the *Vensim DSS* software so as to provide insight into the causal relationships and the dynamics of diabetic health care in South Africa, as well as for the testing of existing intervention strategies for the management of diabetes in South Africa.

Part of the aforementioned system dynamics model relating to the management of the prediabetic population in South Africa was presented in the article titled "*A system dynamics approach to modelling the management of the increased prediabetic prevalence of the South African population.*" at the 25$^{\text{th}}$ annual ICE/IEEE International Technology Management Conference in Sophia Antipolis, France, and consequently published in the 25$^{\text{th}}$ annual ICE/IEEE International Technology Management conference proceedings [115]. The full article citation is as follows: Thomas V, de Kock I & Bam L. (2019). "A system dynamics approach to modelling the management of the increased prediabetic prevalence of the South African population." Proceedings of the *25th ICE/IEEE International Technology Management Conference, 17th–19th of*

June 2019, Sophia Antipolis, Nice, France. ©2019 IEEE. This work was also presented in the form of a poster at the 37^{th} annual International Conference of the System Dynamics Society in Albuquerque, New Mexico. The author's accepted manuscript of the article may be viewed in Appendix D.2.

Another part of the aforementioned system dynamics model relating to the management of the diabetic and diabetic with complications populations in South Africa was presented in the article titled "*A system dynamics approach to modelling the management of diabetes and diabetic complications in South Africa*" at the Sixth Annual South African System Dynamics conference in Johannesburg, South Africa, and consequently published in the Sixth Annual South African System Dynamics conference proceedings [116]. The full article citation is as follows: Thomas V, de Kock I & Bam L. (2018). "A system dynamics approach to modelling the management of diabetes and diabetic complications in South Africa." Proceedings of the *Sixth Annual System Dynamics Conference in South Africa, 22^{th}–23^{th} of November 2018, University of the Witwatersrand, Johannesburg, South Africa*, pp. 57-65. This article may be viewed in Appendix D.3.

Contribution 3 *The identification of causal relationships within the diabetic health care system, as well as policy strategy and intervention recommendations for the management of diabetes in South Africa.*

Based on the analysis of the system dynamics model scenarios results shown in §6.1.2, policy conclusions were formulated and presented in §6.3. These policy conclusions provide insight into the complex and dynamic diabetic health care system and highlight powerful causal relationships between intervention strategies. In addition, these policy considerations may prove useful in further diabetic policy research and the formulation of detailed diabetic polices with alternative interventions to address the management of the diabetes disease in South Africa.

7.3 Limitations

As discussed in §1.5, the focus of this research was on the development of a system dynamics model so as to correctly identify and depict the various causal relationships between stakeholders, resources and patients found within the diabetic health care system in South Africa. Since data relating to the South African health care system, the availability of resources, and various diabetes-related interventions and measures are largely unavailable in South Africa, significantly focus was not placed on the acquisition of largely unavailable data. Although insights on the causal relationship and dynamics of the diabetic health care system, and the high level policy considerations of §6.3 were derived from the system dynamics model scenario results, the use of estimates and assumptions in place of accurate, real-world data prevented the development of detailed policy strategy and intervention recommendations for diabetic policy formulation. The lack of accurate, real-world data available for use in the system dynamics model was, therefore, the most significant limitation of this research.

7.4 Future work

This section details a number of suggestions which may be pursued as follow-up work towards the improvement and enhancement of system dynamics model developed in this research, in fulfilment of Research Objective VIII of §1.4.

The envisioned future work focusses on broadening the research scope and improving the capabilities of the model presented in this thesis, as discussed in §7.4.1 and §7.4.2, respectively. In the case of each suggestion, a brief description and motivation is provided.

7.4.1 Broadening of research scope

This subsection contains three suggestions for future work related to the possible broadening of the research scope presented in this thesis.

Suggestion 1 *The inclusion of other diabetic variations other than type 2 diabetes.*

The system dynamics model, presented in Chapter 5, only considers and investigates type 2 diabetes. Although type 2 diabetes afflicts 95% of those diagnosed with diabetes, the model may benefit from the inclusion of the many variations of diabetes, as discussed in §2.1.2, so as to better represent the real-world diabetic health care system observed in South Africa.

Suggestion 2 *The inclusion of the under eighteen population, as well as the effects of childhood diabetes.*

The current system dynamics model is limited to a population older than eighteen years of age. A model improvement may include the adolescent population so as to model the dynamics of child-onset diabetes on the South African health care system. The model may also benefit from the inclusion of the adolescent population so as to investigate the effect of relatives with type 2 diabetes mellitus on the development of child-onset diabetes, which is shown to be closely related [92].

Suggestion 3 *The consideration of cost or resource allocation in policy recommendations.*

In order to understand the effects of the existing interventions on the diabetic populations, the research scope was limited to modelling the dynamics of the diabetic populations. Any policy strategy and intervention recommendations are, therefore, made based on the effects of the dynamics of the diabetic populations and not with regard to resource allocation or cost of intervention. Policy strategy and intervention recommendations would, however, be improved with the consideration of resource allocation or cost of intervention in this research. Policy strategy and intervention recommendations would, therefore, not only be driven by the most effective strategy to management the diabetic populations in South Africa, but rather the most efficient strategy in managing the diabetic populations with the resources available.

7.4.2 Improved model capabilities

This subsection contains two suggestions for future work related to the improvement of the system dynamics model capabilities presented in this research.

Suggestion 4 *The inclusion of non-fatal diabetic complications.*

The current system dynamics model only considers fatal diabetic complications in modelling the dynamics of the diabetic with complications population in South Africa, and excludes non-fatal complications. The treatment of non-fatal complications, however, consume resources from the health care system in the form of pharmaceuticals or time with a health care professional. Should the consideration of cost or resource allocation be added to the model, as recommended in Suggestion 3, the model may benefit from the inclusion of non-fatal diabetics complications so as to investigate the effect of this inclusion on the South African health care system.

Suggestion 5 *The use of a "Health care system workload" variable to drive the availability of medical resources in the system.*

The system dynamics model, presented in Chapter 5, currently uses the diabetic populations as a driver to influence the availability of medical equipment and pharmaceuticals, the health care professional to patient ratio, the implementation of screening interventions, and the implementation of education interventions. The use of the diabetic populations is to demonstrate the overburdened public health care system and the limit of medical resources available.

As suggested in §5.3.2, the model may benefit from a so-called *Health care system workload* variable that specifically determines the ability of the health care system to supply medical resources, based on the requirements of each diabetic population group and the total available medical resources in the South African health care system. This *Health care system workload* variable may be defined as

$$\frac{a_1 \times \mathit{Prediabetic\ population} + a_2 \times \mathit{Diabetic\ population} + a_3 \times \mathit{Diabetic\ complication\ population}}{Total\ available\ medical\ resources\ available\ in\ South\ African\ health\ care\ system},$$

where a_1, a_2, and a_3 are equal to a constant proportion of resources utilised by a single prediabetic patient, diabetic patient, and diabetic patient with complications, respectively, and medical resources refers to the pharmaceuticals used by a patient and any time spent with a health care professional in a diabetic check-up. This *Health care system workload* variable could then be used as a driver to influence the availability of medical equipment and pharmaceuticals, the health care professional to patient ratio, the implementation of screening interventions, and the implementation of education interventions in the diabetic health care system of South Africa.

7.5 Chapter 7 conclusion

This chapter served as the conclusion of this thesis. Included in this chapter was a summary of the research, together with how the eight research objectives were accomplished. The appraisal of research contributions and limitations were then discussed. Finally, recommendations in terms of possible future follow-up work were presented.

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APPENDIX A

Validation of system dynamics model

This appendix presents the model results of the validation tests discussed in §5.4, so as to further demonstrate the validity of the system dynamics model. The validation tests include the extreme conditions test, integration error test and behaviour reproduction test.

A.1 Extreme conditions test

The extreme conditions tests aims to test the response of the system dynamics model to extreme values of each input and will be applied to various elements of the model, as shown in the sections to follow. Should the model response to the extreme conditions be reasonably similar to the expected real-world observation, the extreme conditions test will be deem the system dynamics model of acceptable validity.

A.1.1 Zero population inflow

In performing this iteration of the extreme conditions test, the population inflow or `South African birth rate` variable is set to zero persons per year. The results of this validation test are shown in Figure A.1. It may be observed in the results of the normal glycemic population stock, undiagnosed deaths auxiliary variable, number of undiagnosed prediabetic stock, and number of diagnosed diabetic stock that as the population inflow is set to zero, the non-diabetic and diabetic population groups, as well as diabetes-related deaths rates, begin to rapidly decrease, as would be expected in the real-world if no new births occurred and the population growth rate decreased to zero.

A.1.2 Significantly increased population inflow

In performing this iteration of the extreme conditions test, the population inflow or `South African birth rate` variable is set to some arbitrary high rate of persons per year. The results of this validation test are shown in Figure A.2. It may be observed in the results of the normal glycemic population stock, undiagnosed deaths auxiliary variable, number of undiagnosed prediabetic stock, and number of diagnosed diabetic stock that that as the population inflow is significantly increased, the non-diabetic and diabetic population groups, as well as

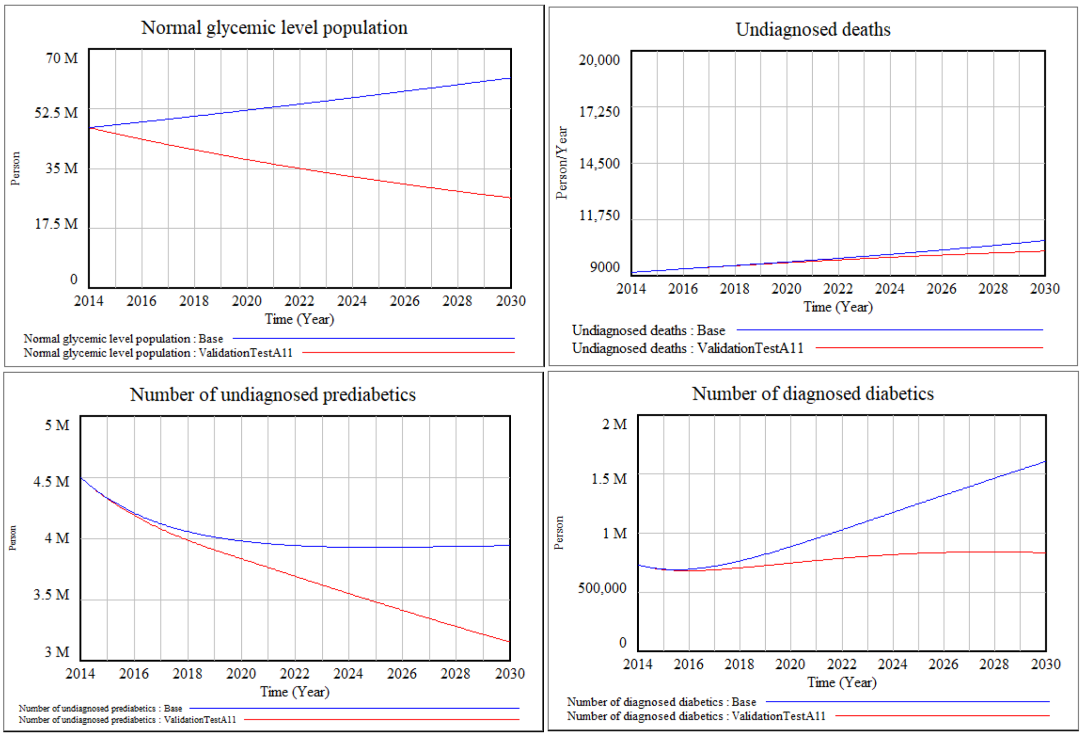

FIGURE A.1: *Extreme conditions test for zero population inflow.*

diabetes-related deaths rates, begin to rapidly increase, as would be expected in the real-world if there was a sudden influx of births worldwide.

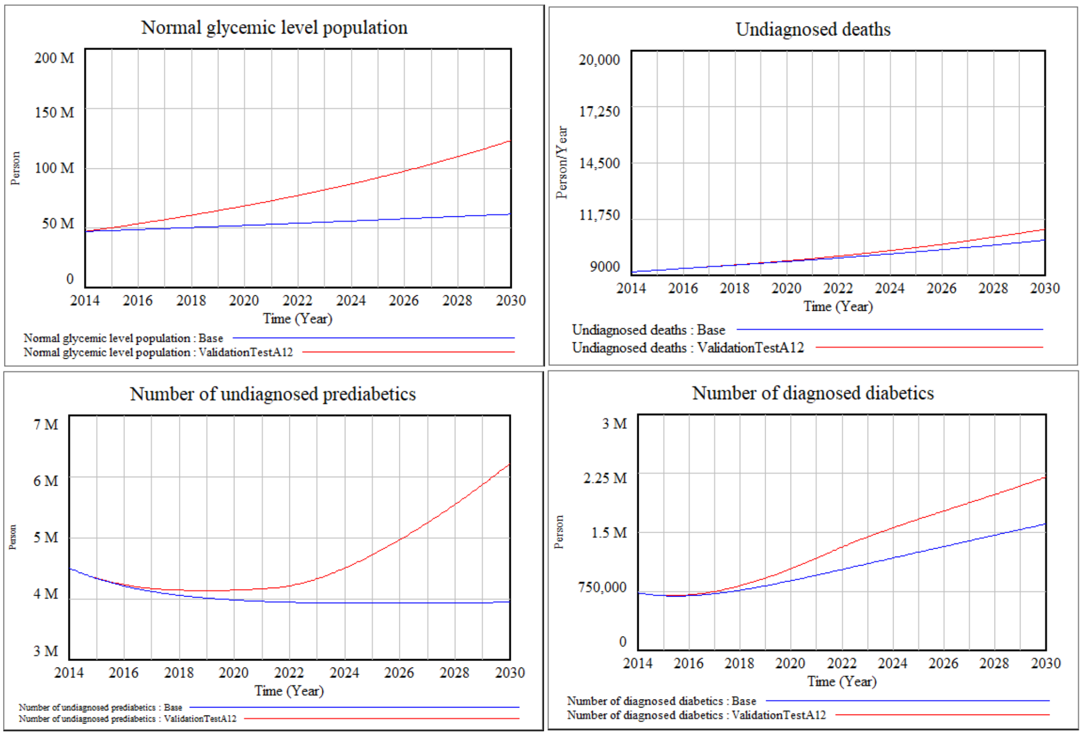

FIGURE A.2: *Extreme conditions test for a significantly increased population inflow.*

A.1.3 Zero initial non-diabetic population

In performing this iteration of the extreme conditions test, the initial non-diabetic population or `Normal glycemic population` stock is set to zero. The results of this validation test are shown in Figure A.3. It is first noted that in the results of the normal glycemic population stock that the non-diabetic population begins at a size of zero and steadily increases at the birth rate. It may, however, be observed in the number of undiagnosed prediabetic stock and number of diagnosed diabetic stock that a rapid decrease in population size takes place, as well as a sudden decrease in death rate, as shown in the undiagnosed deaths auxiliary variable, due to the significant decrease in the non-diabetic population size. These results would, however, we expected in the real-world, because with a smaller population of non-diabetics, the prevalence of diabetes, as well as the rate of diabetes-related deaths, would be decreased due to there being less non-diabetics to develop the disease.

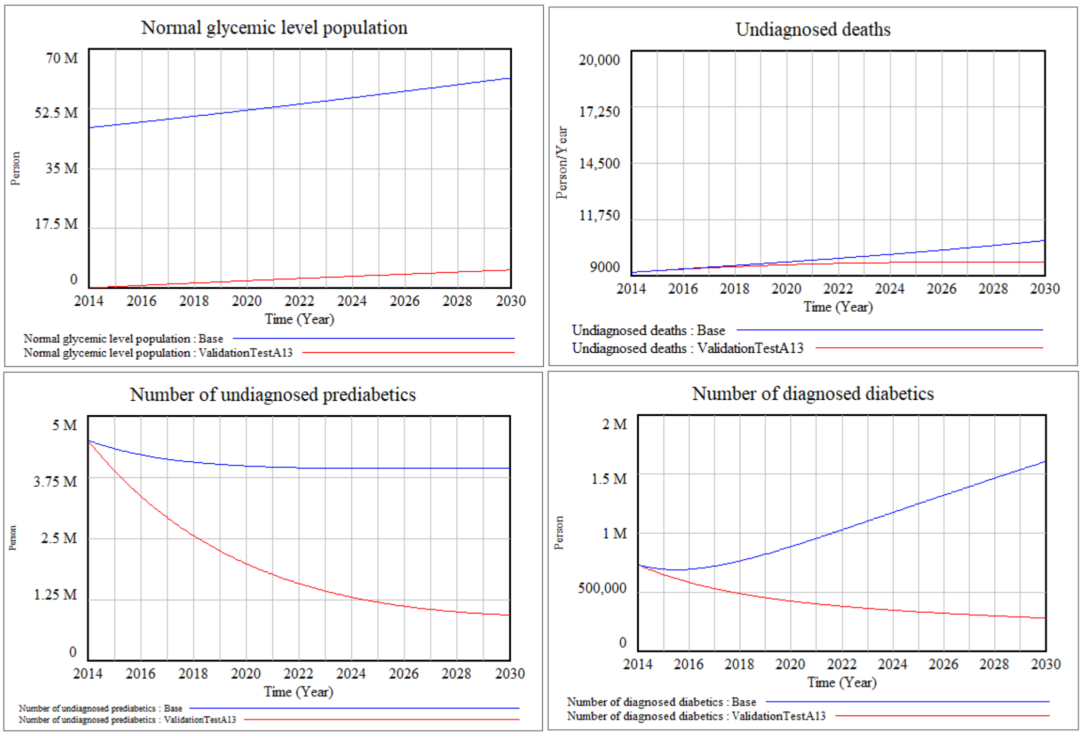

FIGURE A.3: *Extreme conditions test for zero initial non-diabetic population.*

A.1.4 Significantly increased initial non-diabetic population

In performing this iteration of the extreme conditions test, the initial non-diabetic population or `Normal glycemic population` stock is set to some arbitrary large population size. The results of this validation test are shown in Figure A.4. It is first noted that in the results of the normal glycemic population stock that the non-diabetic population begins at significantly higher size and continues to steadily increase at the birth rate. It may, however, be observed in the number of undiagnosed prediabetic stock and number of diagnosed diabetic stock that a rapid increase in population size takes place, as well as a sudden increase in death rate, as shown in the undiagnosed deaths auxiliary variable, due to the significant increase in the non-diabetic population size. These results would, however, we expected in the real-world, because with a larger population of non-diabetics, the prevalence of diabetes, as well as the rate of diabetes-related deaths, would be increased due to there being more non-diabetics to develop the disease.

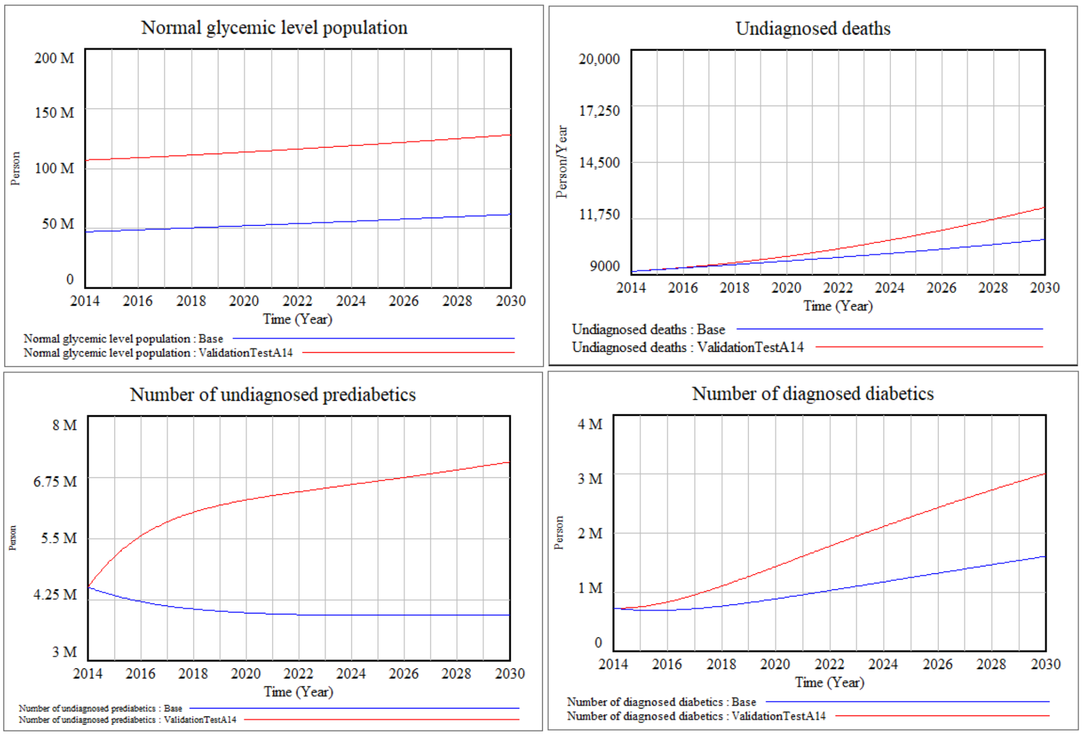

FIGURE A.4: *Extreme conditions test for a significantly increased initial non-diabetic population.*

A.1.5 Significantly decreased diabetic with complications life expectancy

In performing this iteration of the extreme conditions test, the diabetic with complications life expectancy or `Diabetic with complications life expectancy` variable is set to some arbitrary decreased value. The results of this validation test are shown in Figure A.5. It may be observed in the results of the undiagnosed and diagnosed deaths auxiliary variables that as the life expectancy was decreased to a lower age, a significantly higher death rate was observed when compared to the model base results. Consequently, the number of undiagnosed and diagnosed diabetic stocks are decreased, due to the increased death rate, as would be expected in the real-world if the diabetes-related life expectancy were to decrease.

A.1.6 Significantly increased diabetic life expectancy

In performing this iteration of the extreme conditions test, the diabetic with complications life expectancy or `Diabetic with complications life expectancy` variable is set to some arbitrary increased value. The results of this validation test are shown in Figure A.6. It may be observed in the results of the undiagnosed and diagnosed deaths auxiliary variables that as the life expectancy was increased to a higher age, a significantly lower death rate was observed when compared to the model base results. Consequently, the number of undiagnosed and diagnosed diabetic stocks are increased, due to the decreased death rate, as would be expected in the real-world if the diabetes-related life expectancy were to increase.

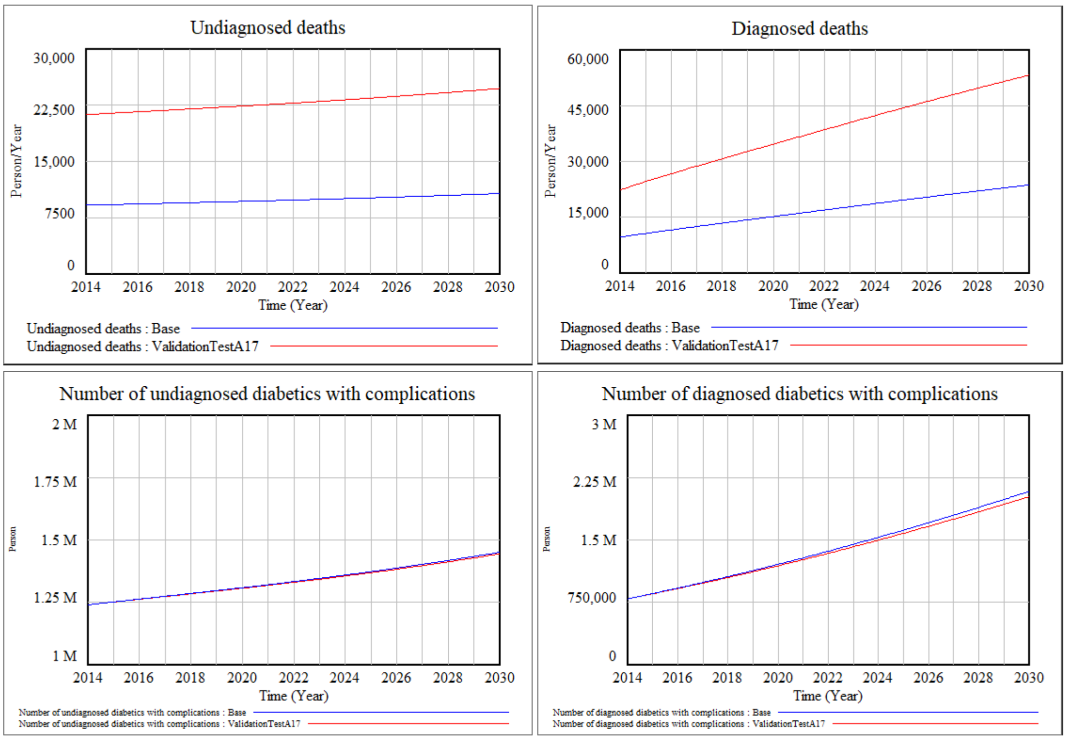

FIGURE A.5: *Extreme conditions test for a significantly decreased diabetic life expectancy.*

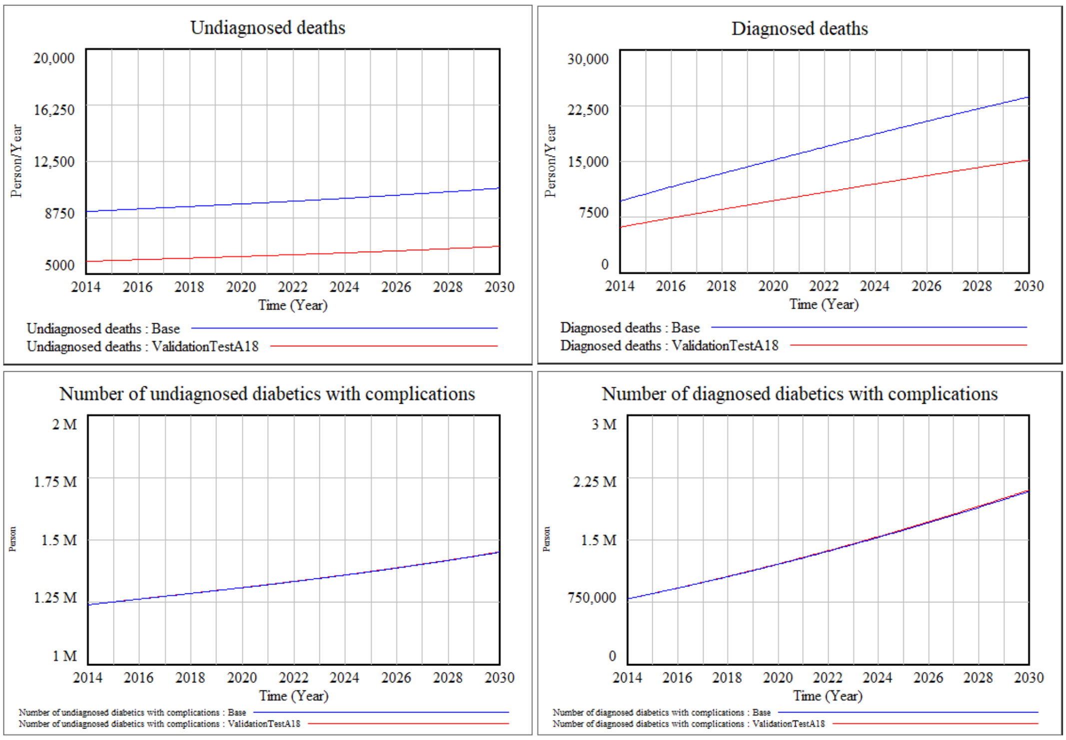

FIGURE A.6: *Extreme conditions test for a significantly increased diabetic life expectancy.*

A.2 Integration error test

In the integration error validation test, Different integration methods, as well as halving the time step of the model, are typically used to test for changes in model output behaviour. As shown in §5.3.6, the system dynamics model makes use of the Euler integration method with a 0.0625 time step. The sections to follow will test for changes in model output behaviour using varying combinations of integration methods, as well as the original and halved time step. Should the model response to the changes in integration method and time step be similar to the base model output, the integration error test will be deem the system dynamics model of reasonable validity.

A.2.1 Euler integration, 0.03125 time step

In performing this iteration of the integration error test, the Euler integration method for the system dynamics model is retained, while a change in time step 0.03125 is tested. The results of this validation test are shown in Figure A.7. It may be observed in the results of the Normal glycemic population stock, Diagnosed deaths auxiliary variable, Number of diagnosed prediabetic stock, and Number of diagnosed diabetic stock that no variance is observed between the base results of the model and this iteration of the integration error test.

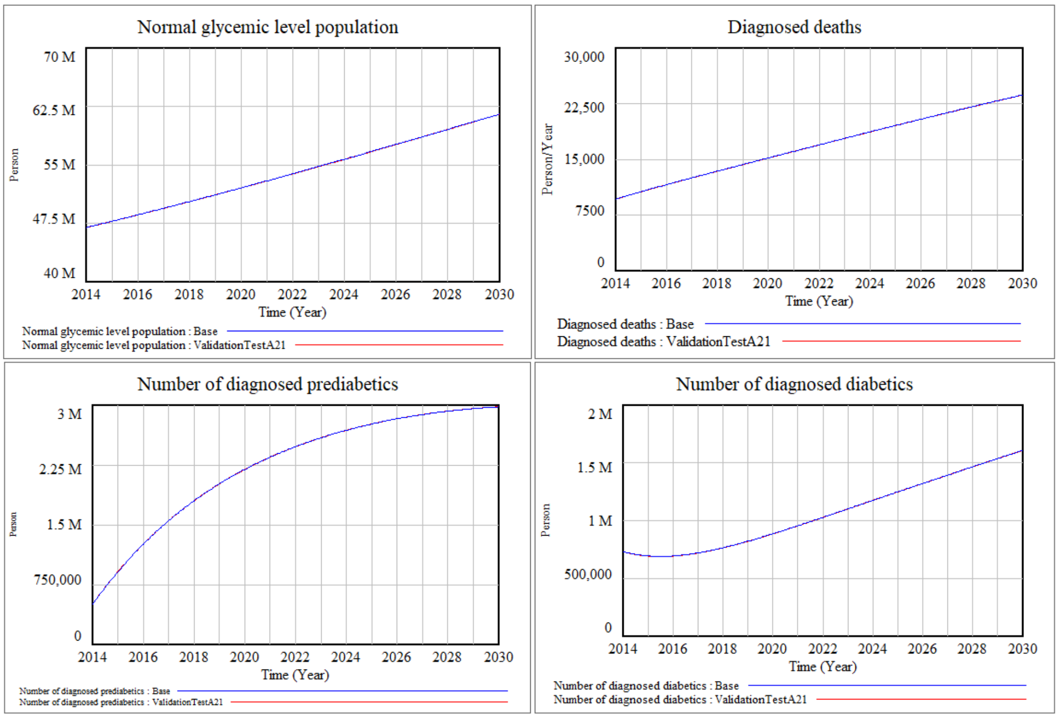

FIGURE A.7: *Integration error test results with Euler integration and 0.03125 time step.*

A.2.2 RK 4 Auto integration, 0.03125 time step

In performing this iteration of the integration error test, the integration method is changed to RK 4 Auto with the time step to 0.03125. The results of this validation test are shown in Figure A.8. It may be observed in the results of the Normal glycemic population stock, Diagnosed deaths auxiliary variable, Number of diagnosed prediabetic stock, and Number of diagnosed diabetic stock that no variance is observed between the base results of the model and this iteration of the integration error test.

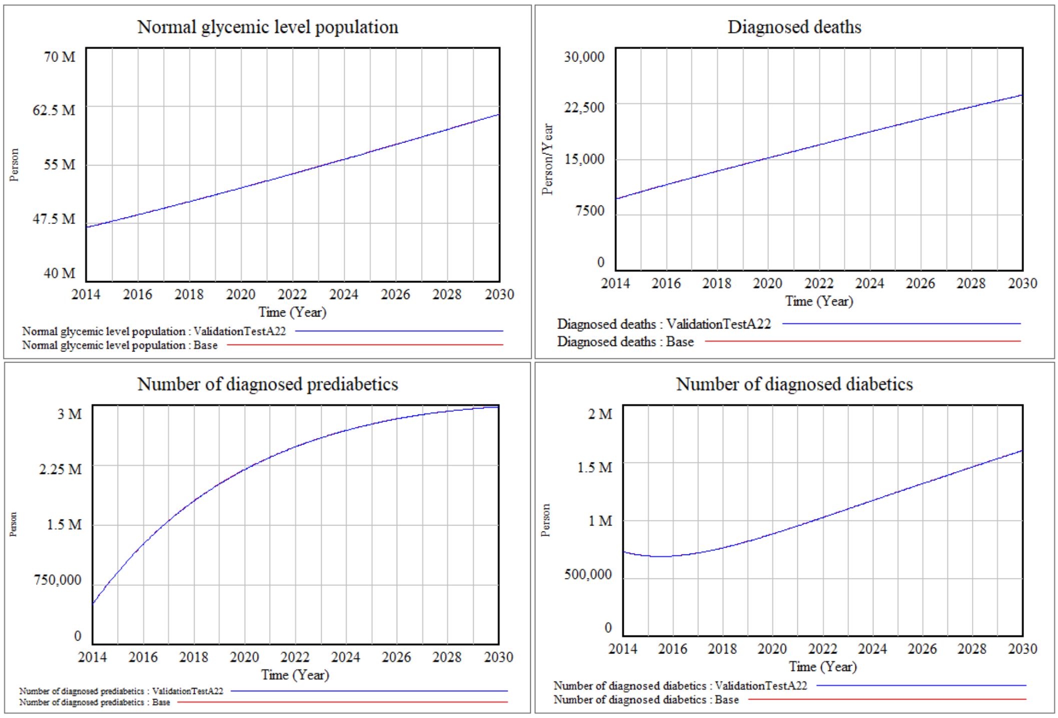

FIGURE A.8: *Integration error test results with RK 4 Auto integration and 0.03125 time step.*

A.2.3 RK 4 Auto integration, 0.0625 time step

In performing this iteration of the integration error test, the 0.0625 time step for the system dynamics model is retained, while a change in integration method to RK 4 Auto integration is tested. The results of this validation test are shown in Figure A.9. It may be observed in the results of the Normal glycemic population stock, Diagnosed deaths auxiliary variable, Number of diagnosed prediabetic stock, and Number of diagnosed diabetic stock that no variance is observed between the base results of the model and this iteration of the integration error test.

A.3 Behaviour reproduction test

The behaviour reproduction test analyses the qualitative comparison between model output and behaviour of the real-world system. Outputs of model elements will be compared to the observations of the real-world system in the sections to follow. Should the qualitative comparison between model output and behaviour of the real-world system be similar, the behaviour reproduction test will deem the system dynamics model of reasonable validity.

A.3.1 South African population

In performing this iteration of the behaviour reproduction test, growth of the South African population is tested, of which the real-world observation of South African population growth

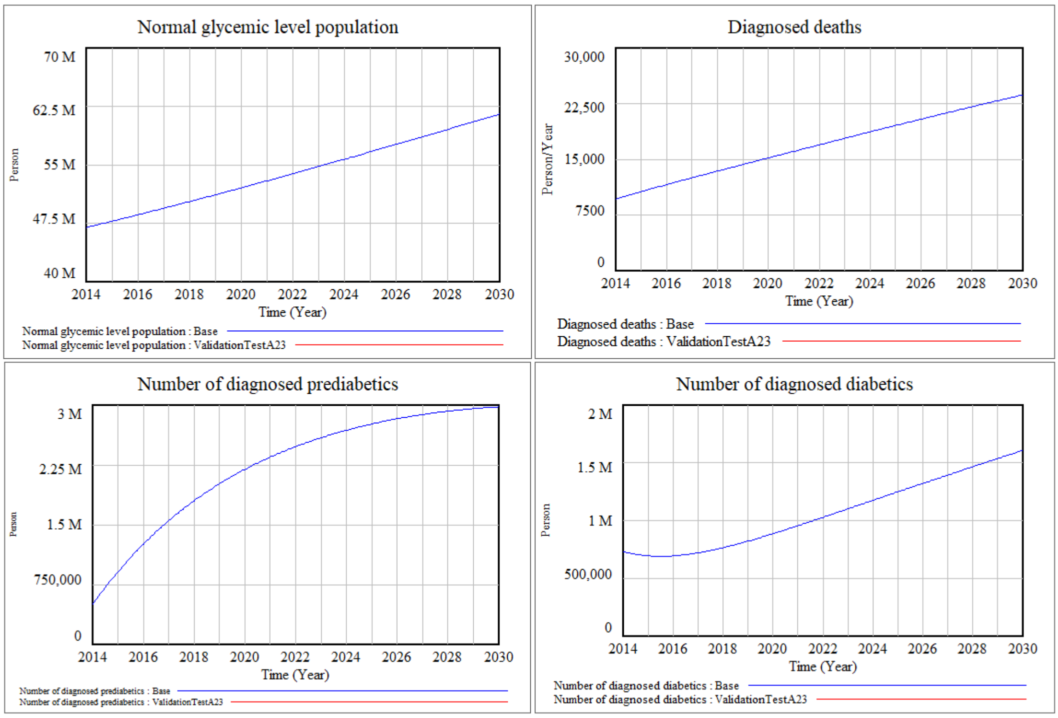

FIGURE A.9: *Integration error test results with RK 4 Auto integration and 0.0625 time step.*

over the time horizon is shown in Figure A.10 [119]. Figure A.11 then displays the model simulation of South African population growth over the time horizon. It may be observed in the real-world observation that the South African population consists of approximately 55 million in 2014 — a population size for 2014 that is found consistent with the model results shown in Figure A.11. It may also be noted that Figure A.10 estimates a South African population of approximately just under 70 million, which is within a reasonable variance for the model simulation of 71.54 million in 2030.

This test does not only demonstrate that the system dynamics model accurately models South African birth and death rates, but also that the complex and dynamic diabetes system developed in the system dynamics model does not alter population estimates, despite the population total consisting of a 7% diabetic prevalence. It is, therefore, argued that the complex system of diabetics, and the dynamics thereof, was modelled with reasonable accuracy.

A.3.2 Diabetes-related deaths

In performing this iteration of the behaviour reproduction test, the number of diabetes-related deaths is tested. Figure A.12 displays the model simulation of the rate of diabetic deaths per year — consisting of both the diagnosed and undiagnosed populations. In the model simulation, it is modelled that a diabetes-related death rate of 10720 undiagnosed persons year and 23670 diagnosed persons per year exists — totalling 34390 diabetes-related deaths per year in 2030. Statistics South Africa estimated that approximately 35000 diabetes-related deaths are predicted for the year 2030 [106]. The real-world observation of the number of diabetes-related deaths may, therefore, be found within a reasonable variance to the model simulation results of the diabetes-related deaths per year.

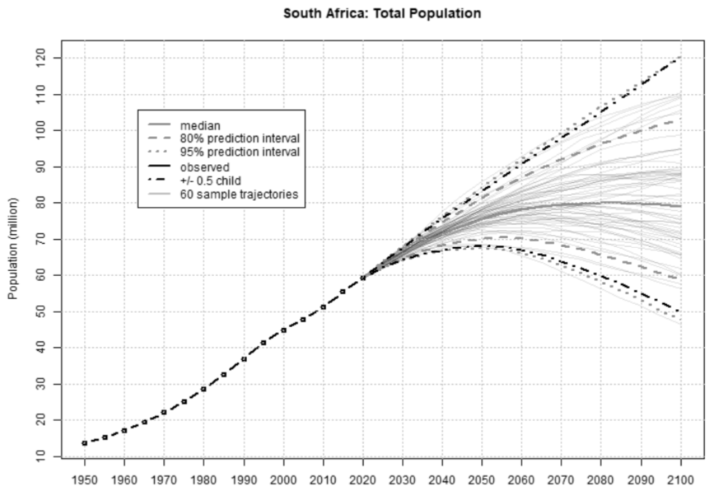

FIGURE A.10: *Real-world observation of population growth over the time horizon [119].*

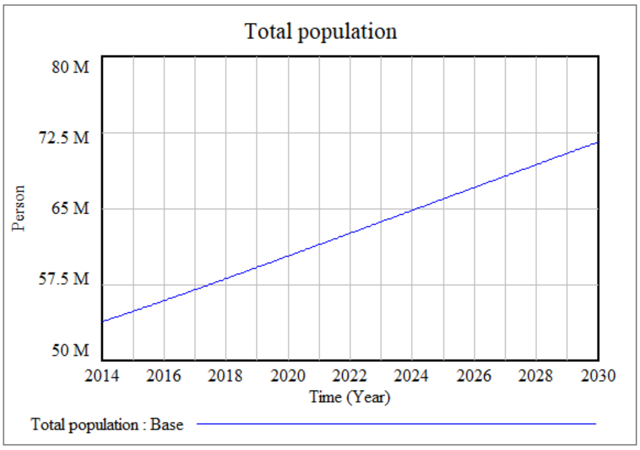

FIGURE A.11: *Model simulation of population growth over the time horizon.*

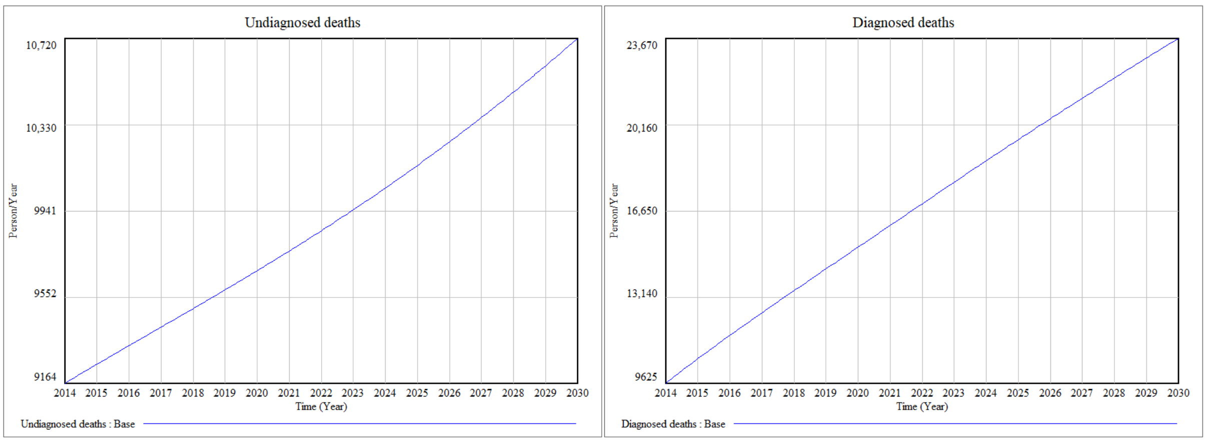

FIGURE A.12: *Model simulation of diabetes-related deaths over the time horizon.*

APPENDIX B

Calculations of intervention variable load increases for scenario testing

This appendix contains the calculations of the range for variable load increase of the *HCPP*, *SMEI*, *LEI*, *SI* and *AMR* interventions to be used in scenario testing, as discussed in §6.1.1.

B.1 Calculation of the range for the *HCPP* intervention variable load

Current population estimates suggest that there are about 55 850 000 South Africans living in the country [130], where approximately 84% rely on public health care [106], which means that the public health care facilities serve $55\,850\,000 \times 0.84 = 46\,914\,000$ South Africans. Furthermore, it is estimated that there are currently 18 000 health care professionals practising in the public health care system [100]. This means that, as of 2019, the *HCPP* ratio in South Africa stands at $46\,914\,000/18\,000 = 0.0003837$ — a finding that is consistent in a recent survey of the public and private health care system [100].

Despite diabetic policy implementation, no baseline or target of the minimum number of health care professionals or the ratio has been set [102, 103]. For the purpose of constructing an appropriate variable load range for the *HCPP* ratio, a baseline target must, however, be set. In order to set a target of the health professional care to patient ratio to be achieved, a country comparable to that of South Africa was identified. From Table 3.1, it is observed that India is a developing country with a diabetic prevalence of 9%. Although the population of India is significantly larger than South Africa, their economic standing and diabetic prevalence is similar. One of the most prominent discussions in the public health domain within context of provision of Universal Health Coverage in India is the shortage of adequate number of health care professionals [59] — a situation also comparable in South Africa. The WHO has consequently set a desirable health care professional to patient ratio for as $1:1000$ or 0.001. It is argued that this target of 0.001 is used as a target for the health care professional to patient ratio in South Africa.

If South Africa was to reach the targeted 0.001 *HCPP* ratio by 2030 (in accordance with the end of the model time horizon), assuming that the South African population grows by annual 2.07% annually [127], then this ratio must increase by an optimistic 9.10% per annum, as shown in Table B.1. This serves as an upper bound of the *HCPP* variable load. The base case is if zero growth for the *HCPP* ratio is experienced. By interpolating between the base case and the upper bound and assuming three fixed intervals (corresponding to a "low", "medium" and "high" scenario), a lower bound of $9.10\% \times 1/3 = 3.03\%$ may be established. The variable load range for the *HCPP* ratio is defined as and rounded to 3%–9%.

Table B.1: *Optimistic annual growth in the health care professional to patient ratio.*

Year	South African population	Health care professional to patient ratio	Number of health care professionals
2019	46914000	0.0003837	18000
2020	47885120	0.0004186	20044
2021	48876342	0.0004567	22321
2022	49888082	0.0004982	24856
2023	50920765	0.0005436	27679
2024	51974825	0.000593	30822
2025	53050704	0.000647	34323
2026	54148854	0.0007059	38221
2027	55269735	0.0007701	42562
2028	56413818	0.0008402	47396
2029	57581584	0.0009166	52779
2030	58773523	0.001	58773

B.2 Calculation of the range for the *SMEI* and *LEI* intervention variable loads

In Cape Town, a project called the *Diabetes Lifestyle Education Collaboration and Action* (DLECA) project is currently being offered, where the aim of this project is to improve diabetes care through the provision of group diabetes education at primary care level, as well as advocate for DLECA nationally and to support its implementation across South Africa. This project is set to run between 2018–2020, and is currently aims to teach 480 courses targeted at 7 200 diabetic patients in the Cape Town area at 80 PHC institutes, where 160 health care professionals were trained as facilitators in group diabetes education [131]. The DLECA course is composed of four sessions (typically held on a monthly basis) designed to be led by a facilitator for approximately 2 hours with a maximum of 15 patients in a group [131]. In broad terms, the four sessions provide eduction relating to both self-management and lifestyle with a particular focus on (i) what is diabetes, (ii) lifestyle changes, (ii) understanding diabetic medication, and (iv) controlling diabetes and avoiding complications [131]. For this project to succeed, each health care professional must teach the DLECA programme for approximately $(4\ sessions\ per\ course\ \times 2\ hours\ \times 480\ courses\ )/(160\ health\ care\ professionals\ \times 2\ years) =$ 12 hours every year.

Since there is no documented standard for implementing self management and lifestyle education in a South African context, a base case for the variable load range must first be established. A optimistic standard for South Africa would thus be to ensure that all diabetics complete the DLECA course by the end of the time horizon — a goal that is in line with the *American Diabetes Self Management Education and Support* national standards [46].

As previously mentioned, there are approximately 18 000 practising health care professionals in the public health care system [100]. The data on the net changing rate of the incoming and outgoing health care professionals in South Africa is, however, unavailable. The South African growth rate of 2.07% is, therefore, used as a proxy [127]. Although this method may seem unconventional, it is fairly conservative considering approximately one thousand new medical interns currently enter the health system per year. As of 2019, there is an estimated 3 910 000 people living in South Africa with either diagnosed or undiagnosed diabetes [47]. If the DLECA program was to be implemented nationally, assuming that the South African diabetic population continues to grow by 1.96% annually [102] and each health care professional is trained to be a DLECA facilitator teaching approximately 12 hours per year, all diabetics living in South Africa would have completed the course by 2029, as shown in Table B.2. This scenario forms the base case for the for the *SMEI* and *LEI* variable load ranges. Using this result, lower and upper variable load bounds are established by considering a “low” and “high” scenario in which all diabetics complete the DLECA course by years 2028 and 2026, respectively, where year 2027 corresponds to a “medium” scenario. The “low” scenario requires that all health care professionals teach 13.07 hours per year which is 8.91% more than the base scenario while the “high” scenario requires a 40.18% increase in the total hours worked per health care professional. The variable load range for the *SMEI* and *LEI* interventions are both be defined as and rounded to 9%–40%.

Table B.2: *Optimistic annual growth in the implementation of self management and lifestyle education interventions.*

		Base		**Low**		**High**	
		Hours per Health care professional	12	**Hours per Health care professional**	13.07	**Hours per Health care professional**	16.82
		% of base	100%	**% of base**	108.91%	**% of base**	140.18%
Year	**Health care professionals**	**Uncompleted**	**Completed**	**Uncompleted**	**Completed**	**Uncompleted**	**Completed**
2019	18000	3910000	405000	3910000	441104	3910000	567730
2020	18373	3581718	413393	3545614	450245	3418988	579495
2021	18753	3238602	421943	3164938	459557	2906577	591481
2022	19141	2880204	430673	2767480	469065	2372126	603718
2023	19537	2506044	439583	2352716	478770	1814952	616208
2024	19941	2115632	448673	1920109	488670	1234355	628951
2025	20354	1708470	457965	1469114	498791	629623	641977
2026	20775	1284027	467438	999149	509108	0	
2027	21205	841783	477113	509645	519645		
2028	21644	381187	388666	0			
2029	22092	0					

B.3 Calculation of the range for the *SI* intervention variable load

It is widely accepted that screening should be targeted at individuals over the age of 45 years [102, 103]. The number of undiagnosed diabetics over the age of 45 years, therefore, needs to first be determined. The 2014 mid–year population estimates by Statistics South Africa provides a breakdown of the South African population based on age and ethnicity. Using prevalence of diagnosed diabetes for the South African population ethnicity and gender groups [52] in conjunction with the population estimates from Statistics South Africa, the total number of diagnosed diabetics per age group in South Africa are determined. In Table 5.2, it is shown that the sum of the initial values for *Number of undiagnosed diabetics* and *Number of undiagnosed diabetics with complications* results in 2.39 million undiagnosed diabetics in South Africa. Using the proportions of diagnosed diabetics per age group with the total number of undiagnosed diabetics in South Africa, it is calculated that approximately 2 102 628 undiagnosed diabetics over the age of 45 years exists in South Africa.

If all diabetics over the age of 45 receive the appropriate screened procedure by the end of 2030, assuming that the South African diabetic population continues to grow by 1.96% annually [102], this would be achieved if 121 604 of these diabetics are screened each year, as shown in Table B.3. This scenario forms the base case for the for the *SI* variable load range. Using this result, lower and upper variable load bounds are established by considering a "low" and "high" scenario in which all diabetics are screened by years 2029 and 2027, respectively, where year 2028 corresponds to a "medium" scenario. The "low" scenario requires that 128 520 diabetics over the age of 45 are screened each year which is 5.69% more than the base scenario while the "high" scenario requires a 19.70% increase in over 45 patient screening per annum. The variable load range for the *SI* interventions may, therefore, both be defined as and rounded to 6%–20%.

Table B.3: *Optimistic annual growth in the implementation of the screening intervention.*

	Base		Low		High	
	Diabetics screened	121604	**Diabetics screened**	121604	**Diabetics screened**	145566
	% of base	100%	**% of base**	105.69%	**% of base**	105.69%
Year	**Unscreened diabetics**	**Number of diabetics screened**	**Unscreened diabetics**	**Number of diabetics screened**	**Unscreened diabetics**	**Number of diabetics screened**
2014	2102628	121604	2102628	128520	2102628	145566
2015	2022280	121604	2015364	128520	1998318	145566
2016	1940355	121604	1926388	128520	1891960	145566
2017	1856822	121604	1835666	128520	1783516	145566
2018	1771650	121604	1743164	128520	1672944	145566
2019	1684808	121604	1648847	128520	1560202	145566
2020	1596261	121604	1552679	128520	1445249	145566
2021	1505977	121604	1454624	128520	1328040	145566
2022	1413921	121604	1354646	128520	1208531	145566
2023	1320059	121604	1252705	128520	1086677	145566
2024	1224356	121604	1148765	128520	962432	145566
2025	1126775	121604	1042785	128520	835750	145566
2026	1027279	121604	934726	128520	706581	145566
2027	925831	121604	824546	128520	574879	
2028	822392	121604	712205	128520		
2029	716924	121604	597660			
2030	609386					

B.4 Calculation of the range for the *AMR* intervention variable load

Supply chain management for pharmaceuticals in the public health care system often relies on medicine being procured centrally and distributed through several steps to the stock facilities [103]. Due to predominantly paper-based system, as well as the underinvestment in information and communication technologies, issues with the availability and documentation of pharmaceuticals continue. Consequently, accurate data on the stock outs of pharmaceuticals and equipment from a public sector perspective are not available. The *Stock Visibility Solution* (SVS) was implemented by Mezzanine in order to address this issue [76]. The SVS uses smart phone and application bundles in dispensing facilities to capture the stock levels of pharmaceuticals daily [76]. The information is synchronised to a cloud-hosted server in real time so as to automate alerts and reports in support of various levels of the supply chain management.

Since there is no documented standard for the availability of medical resources in a South African context, a base case for the variable load range must first be established. A optimistic standard for South Africa would thus be to ensure that the appropriate diabetic medication is sufficiently available after the complete adoption of SVS. For this research, the availability of two diabetic pharmaceutical are considered: Metformin tablets and short-acting insulin injectables. According to the 2017 Stop Stock out Annual Report, the Metformin tablets are almost always available at clinics accross South Africa at 99.07% [108]. The issue arises with the more frequently used short-acting insulin injectables which have an average availability of 96.32% [108]. An appropriate standard may, therefore, be to ensure short-acting insulin injectables also maintain at least a 99% availability.

Mezzanine started the implementation of their SVS in 2014 [27], and had implemented the solution in 1 800 clinics by 2016, 3 100 clinics by 2017 [27], and 3 300 clinics by 2019 [76]. A logarithmic regression line of $y = 1936.19\ln(x) - 20.11$ is fitted to this data to project that all 4 200 clinics in South Africa would be using the SVS by 2022. If the availability of the short-acting insulin injectables improves by 22.93%, then a 99% availability can be achieved by 2022, as shown in Table B.4. This improvement rate is reasonable since, following implementation of SVS in the province of KwaZulu-Natal, Mezzanine reported that annual stock outs for ARVs and TB medicines decreased by 46% and 49%, respectively [27]. This scenario forms the base case for the for the *AMR* variable load range. Using this result, lower and upper variable load bounds are established by considering a "low" and "high" scenario in which a 99% short-acting insulin injectables availability is achieved by 2021 and 2019, respectively, where 2020 corresponds to a "medium" scenario. The "low" scenario requires that a 27.79% improvement is maintained while the "high" scenario requires a 47.86% improvement. The variable load range for the *AMR* intervention may, therefore, be defined and rounded to 28%–48%.

Table B.4: *Optimistic annual growth in the availability of medical resources.*

	Growth		
Year	**Base**	**Low**	**High**
2017	96.32%	96.32%	96.32%
2018	97.17%	97.34%	98.08%
2019	97.82%	98.08%	99.00%
2020	98.32%	98.62%	
2021	98.70%	99.00%	
2022	99.00%		

APPENDIX C

System dynamics model results

This appendix contains the undiagnosed and diagnosed diabetic deaths per year model results of the scenario testing discussed in §6.1.2. Figures C.1 — C.25 present the model testing results of scenarios 7 — 31, respectively, as captured in Table 6.3.

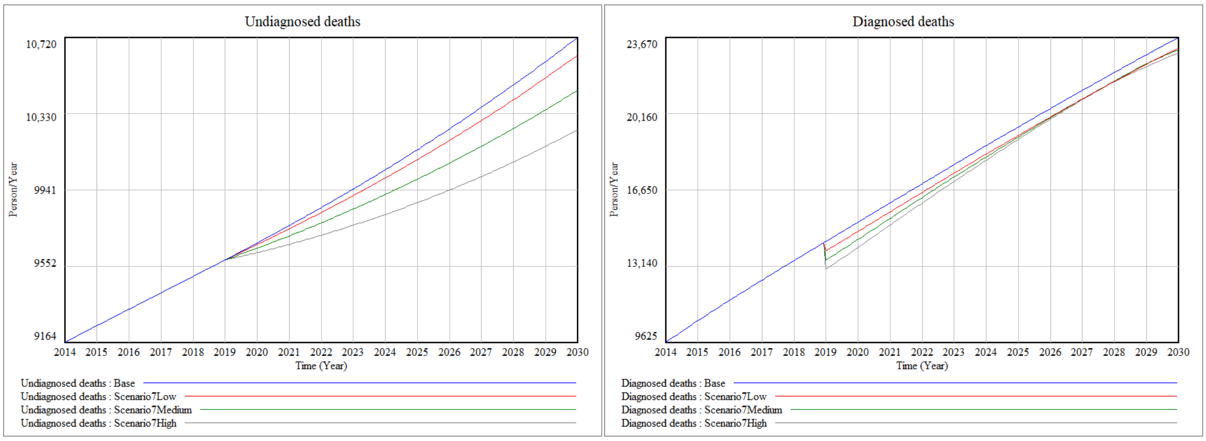

FIGURE C.1: *System dynamics model results of scenario 7.*

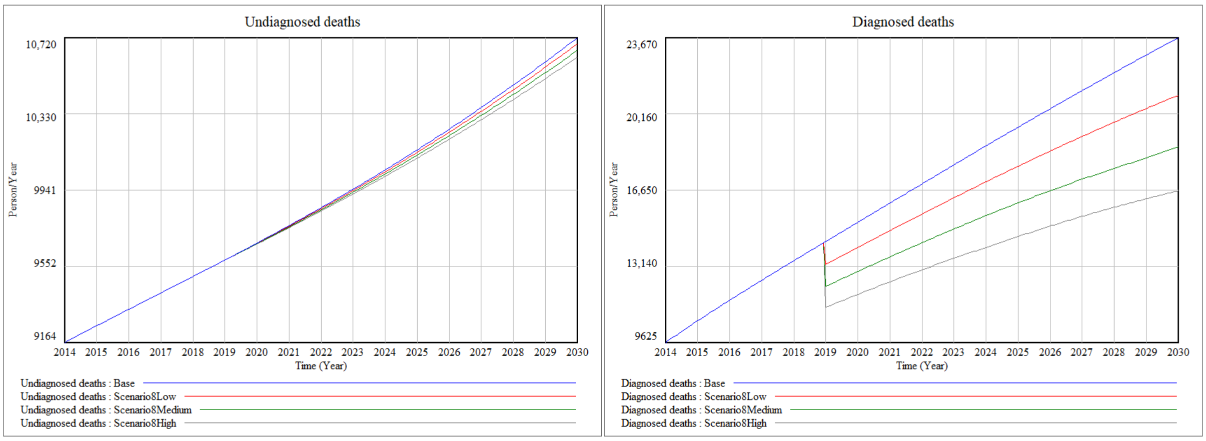

FIGURE C.2: *System dynamics model results of scenario 8.*

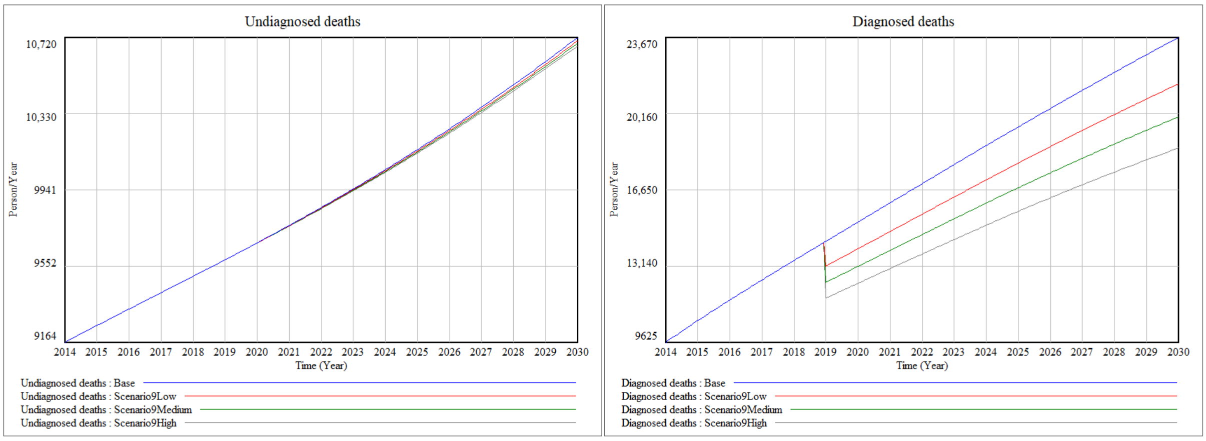

FIGURE C.3: *System dynamics model results of scenario 9.*

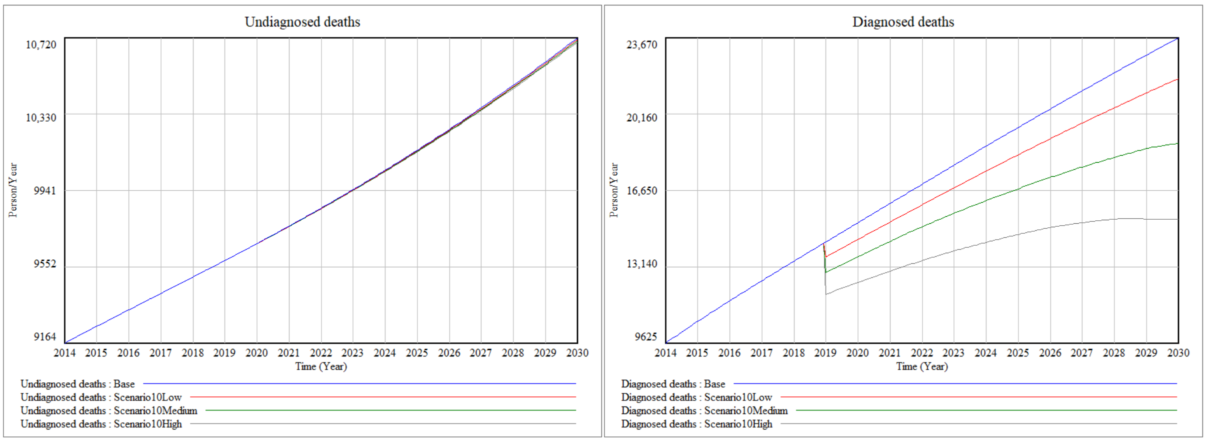

FIGURE C.4: *System dynamics model results of scenario 10.*

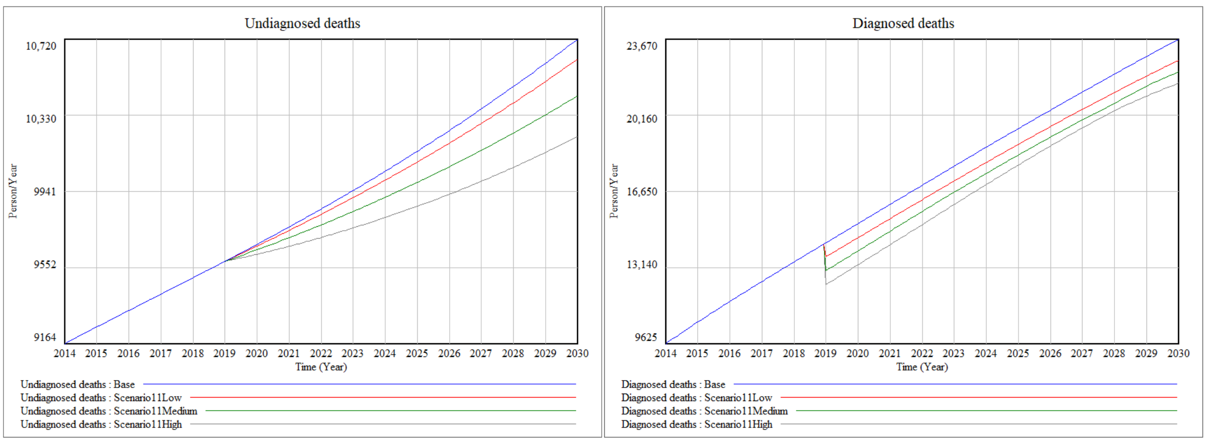

FIGURE C.5: *System dynamics model results of scenario 11.*

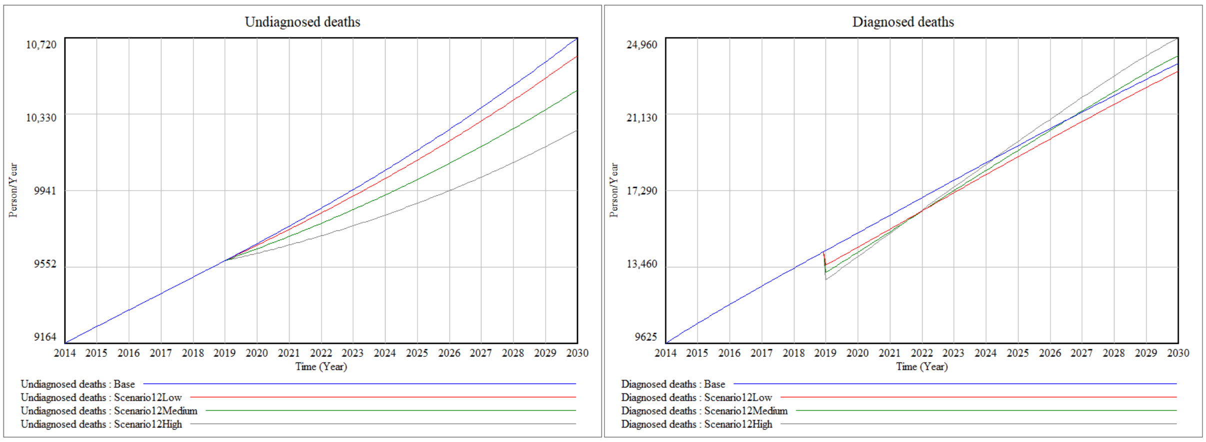

FIGURE C.6: *System dynamics model results of scenario 12.*

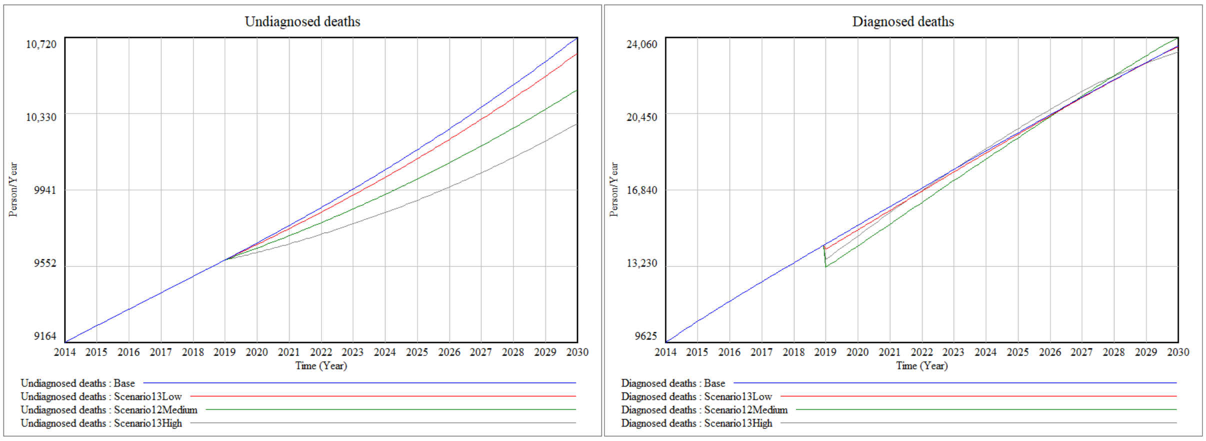

FIGURE C.7: *System dynamics model results of scenario 13.*

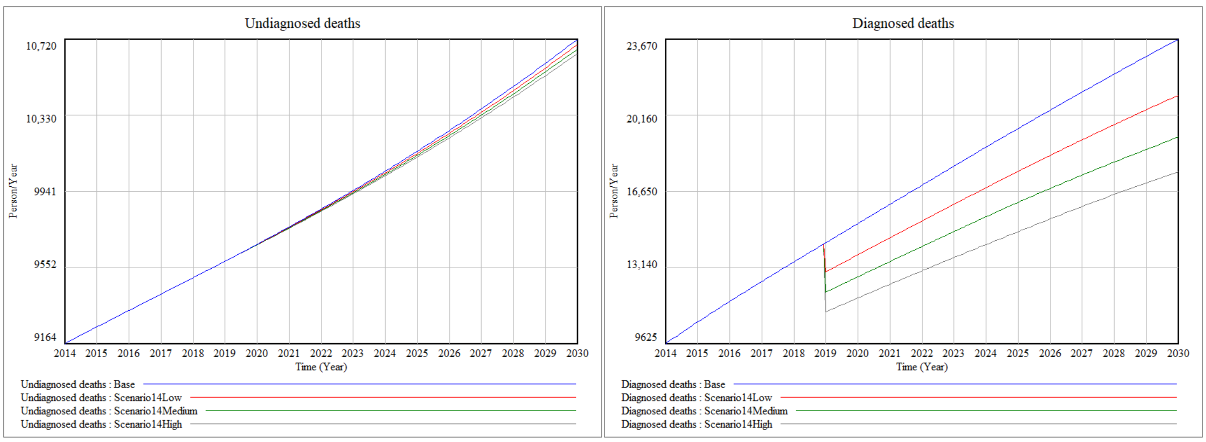

FIGURE C.8: *System dynamics model results of scenario 14.*

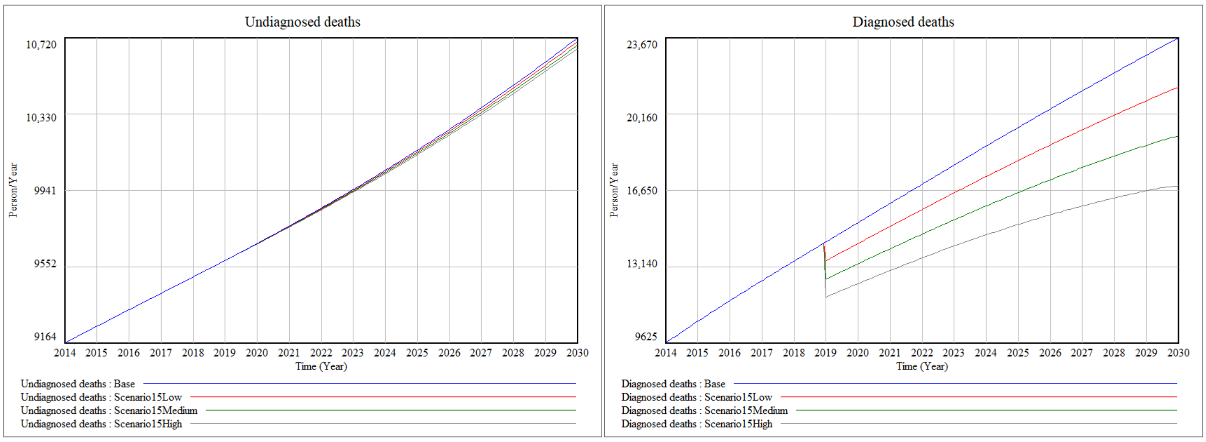

FIGURE C.9: *System dynamics model results of scenario 15.*

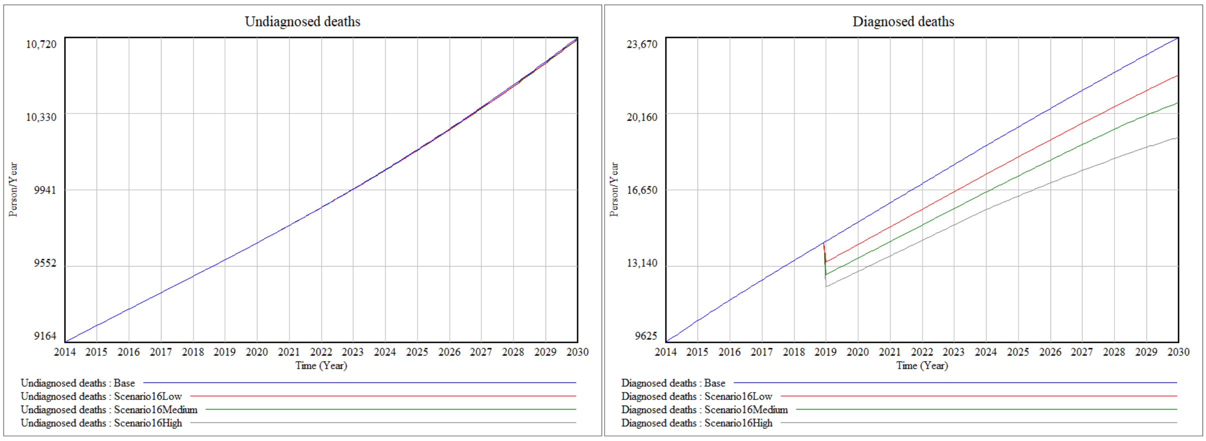

FIGURE C.10: *System dynamics model results of scenario 16.*

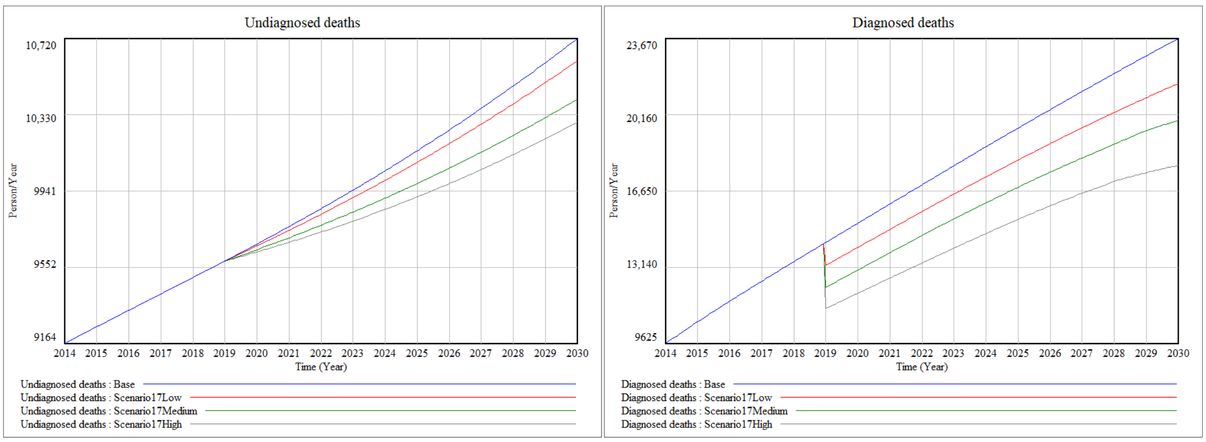

FIGURE C.11: *System dynamics model results of scenario 17.*

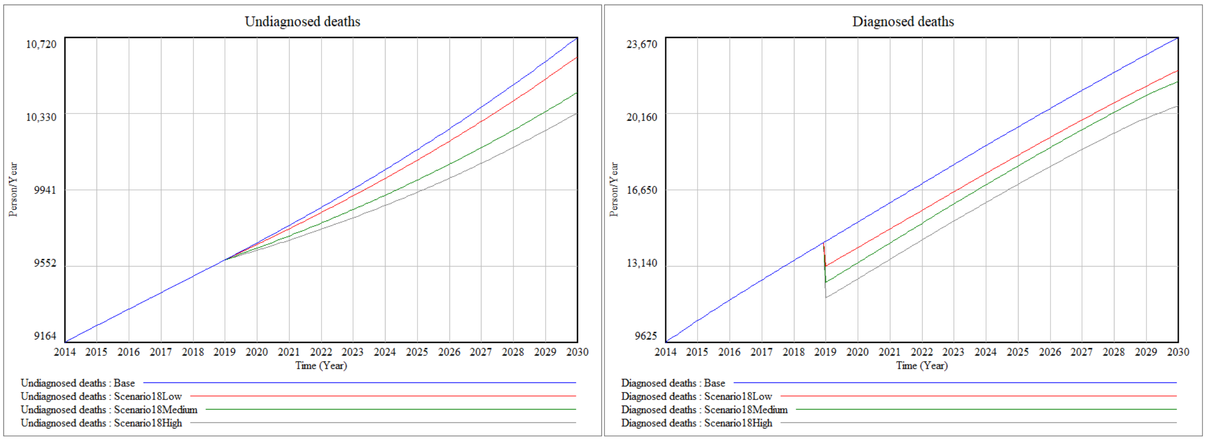

FIGURE C.12: *System dynamics model results of scenario 18.*

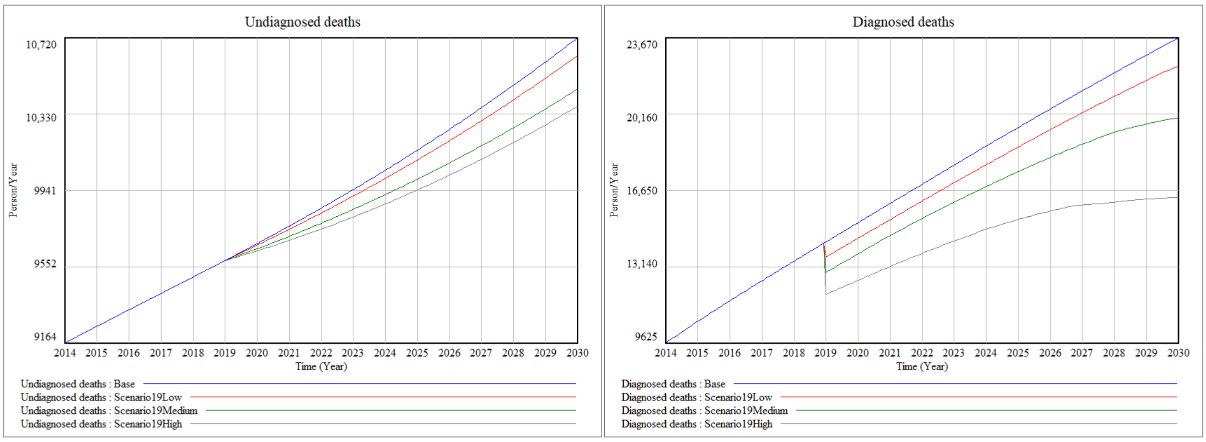

FIGURE C.13: *System dynamics model results of scenario 19.*

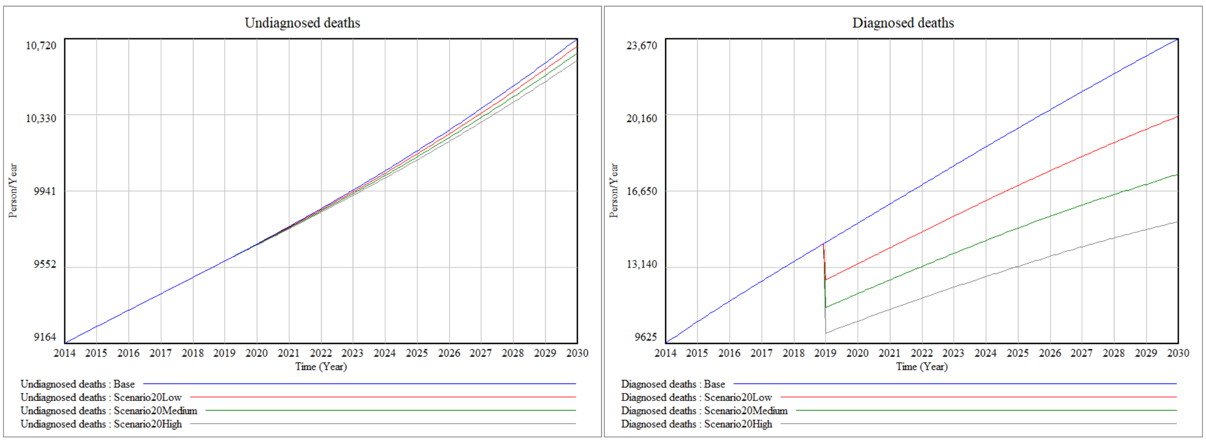

FIGURE C.14: *System dynamics model results of scenario 20.*

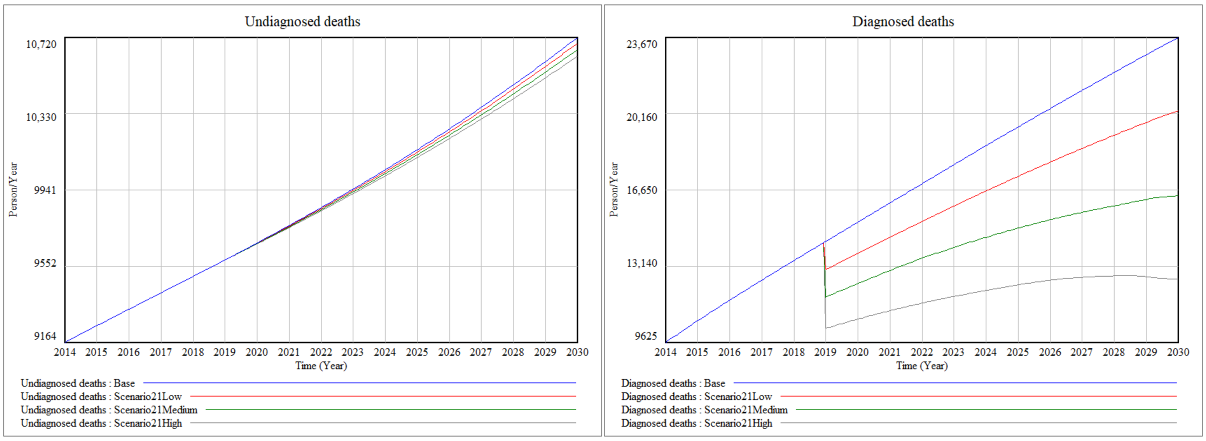

FIGURE C.15: *System dynamics model results of scenario 21.*

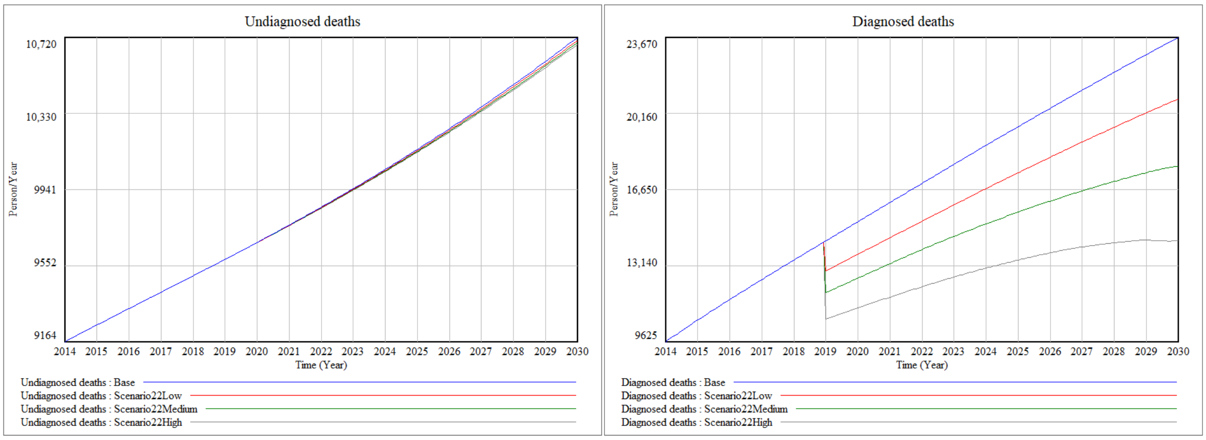

FIGURE C.16: *System dynamics model results of scenario 22.*

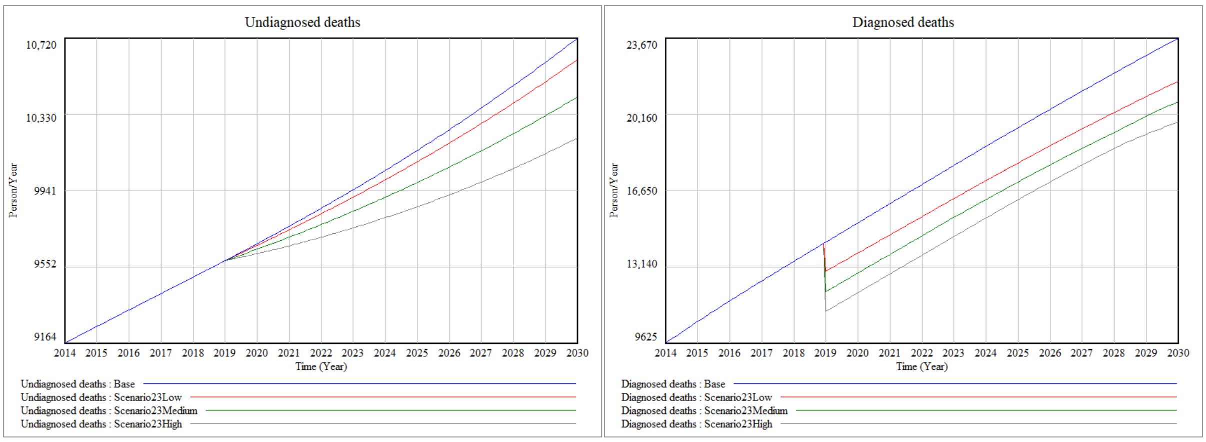

FIGURE C.17: *System dynamics model results of scenario 23.*

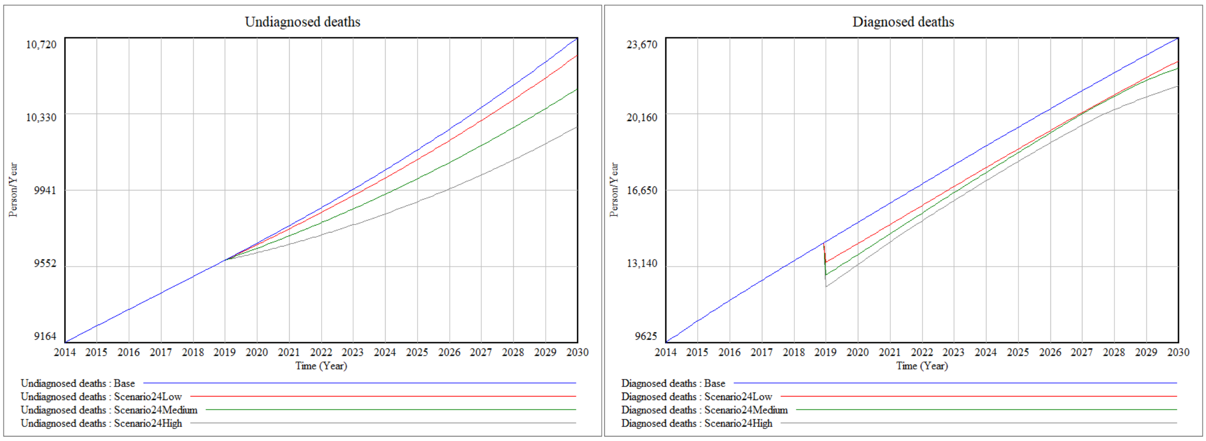

FIGURE C.18: *System dynamics model results of scenario 24.*

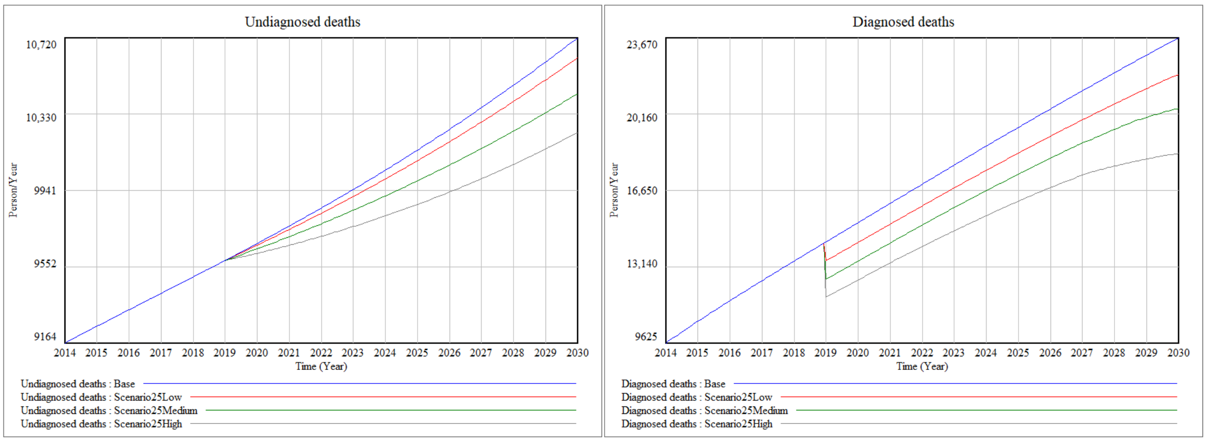

FIGURE C.19: *System dynamics model results of scenario 25.*

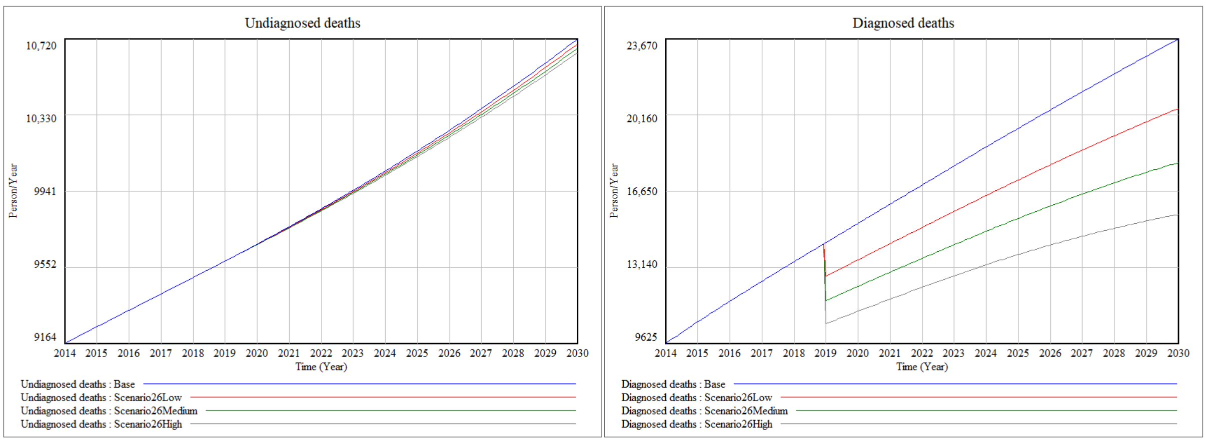

FIGURE C.20: *System dynamics model results of scenario 26.*

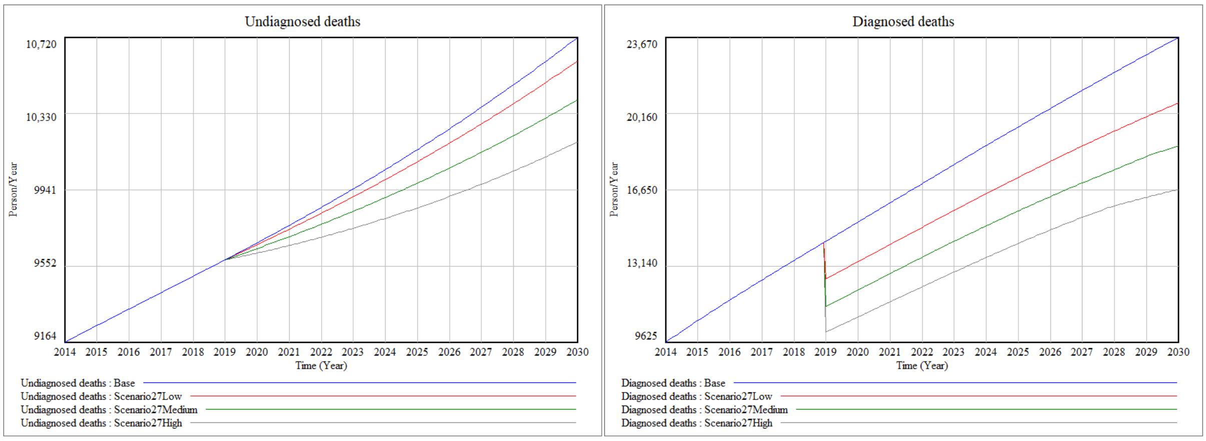

FIGURE C.21: *System dynamics model results of scenario 27.*

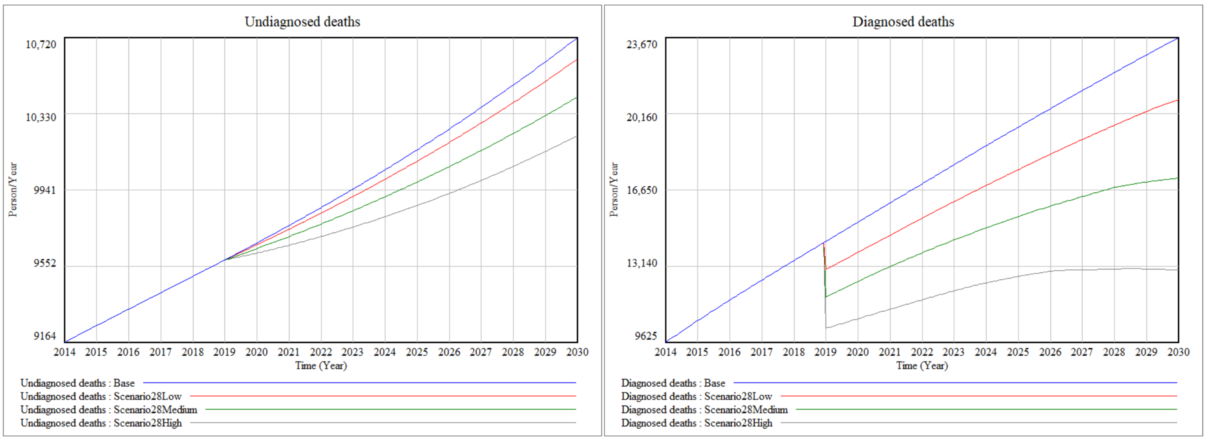

FIGURE C.22: *System dynamics model results of scenario 28.*

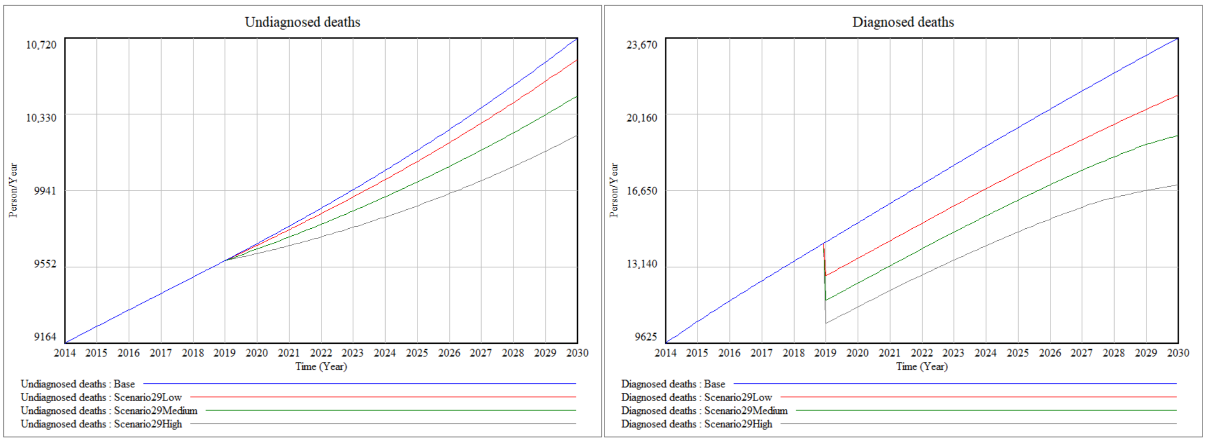

FIGURE C.23: *System dynamics model results of scenario 29.*

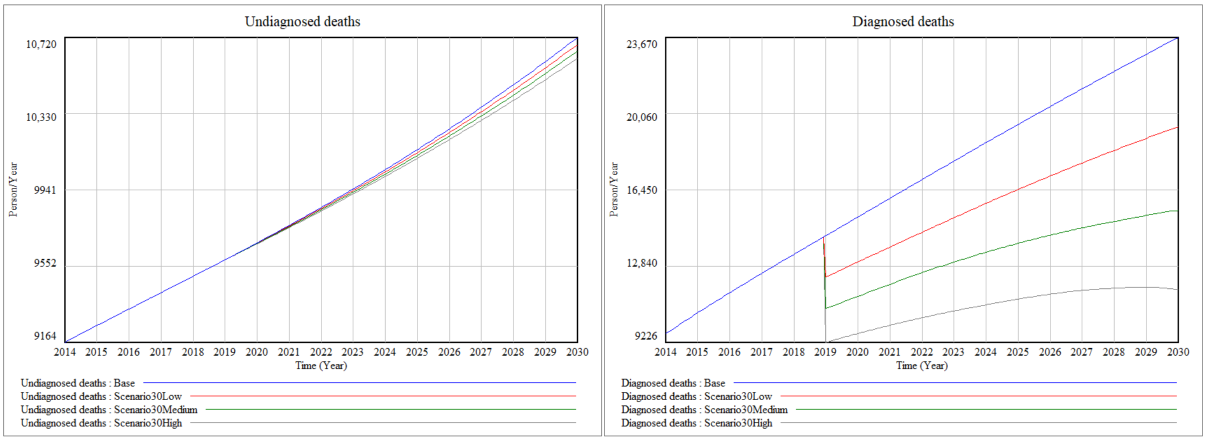

FIGURE C.24: *System dynamics model results of scenario 30.*

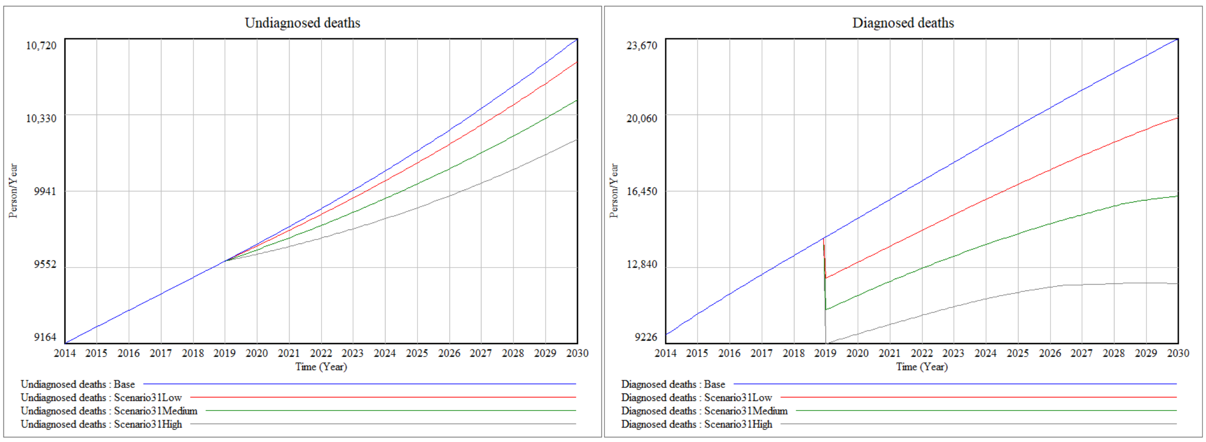

FIGURE C.25: *System dynamics model results of scenario 31.*

APPENDIX D

Conference proceedings

This appendix contains the conference proceedings of work completed as part of this research, as discussed in §7.2.

D.1 Considering the need for alternative intervention strategies for the management of diabetic policy formulation in South Africa

This section contains the article "*Considering the need for alternative intervention strategies for the management of diabetic policy formulation in South Africa*", of which the full article citation is as follows: Thomas V, de Kock I & Bam L. (2018). "Considering the need for alternative intervention strategies for the management of diabetic policy formulation in South Africa." Proceedings of the *SAIIE29 Conference, 24th–26th of October 2018, Spier, Stellenbosch, South Africa*, pp. 295–306.

SAIIE29 Proceedings, 24th – 26th of October 2018, Stellenbosch, South Africa © 2018 SAIIE

CONSIDERING THE NEED FOR ALTERNATIVE INTERVENTION STRATEGIES FOR THE MANAGEMENT OF DIABETIC POLICY FORMULATION IN SOUTH AFRICA

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ABSTRACT

The increasing prevalence of diabetes in South Africa, alongside other non-communicable diseases, places a heavy burden on the health care system; especially when faced with the significant difference in quality of care between private and public health care, and the increased burden of disease.

This paper analyses various diabetic policies already implemented in South Africa, and considers the need to investigate alternative policies and intervention strategies to manage diabetes in South Africa. Due to the complex nature and non-linear interactions which exist within the health care system, a system dynamics-based approach is suggested as a useful analysis tool to evaluate and understand the dominant factors that influence the effective management of diabetes to potentially inform more effective and efficient diabetic policy formulation.

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1. INTRODUCTION

The increasing prevalence of diabetes mellitus (commonly referred to as diabetes) in the world is a widespread concern [1]. According to predictions by the International Diabetes Federation, the prevalence of diabetes is expected to globally increase from 415 million in 2015 to 642 million in 2040 [2, 3]. While improvement has been made in the epidemiology and management of diabetes in the developed world [1], the same advances have not been made in sub-Saharan Africa. Sub-Saharan Africa, similarly to the rest of the world, is experiencing an increasing prevalence of diabetes alongside other non-communicable diseases [3]. In South Africa, this diabetic trend is still emergent in a region confronted with high rates of communicable diseases, such as HIV, as well as Tuberculosis [4].

Additionally, diabetes plays a significant role in contracting several other (often life threatening) diseases [4]. These diseases include both non-communicable diseases, such as cardiovascular disease and renal disease, and communicable diseases, such as pneumonia and tuberculosis, which have a considerable impact on morbidity and mortality in sub-Saharan Africa [4]. In addition, the prevention and treatment of diabetes is a significantly complex process, involving numerous role-players and stakeholders (i.e. government agencies, the healthcare system, communities and diabetic patients). It is, therefore, necessary to also consider diabetic health care in South Africa from a complex, system's perspective, with significant non-linear interactions. With the increasing burden of disease in South Africa, as well as limited resources and the complex, dynamic nature of the healthcare system, it is unsurprising that the prevalence for diabetes in South Africa continues to increase [1, 4].

In order to highlight the need to investigate alternative diabetic intervention and management strategies, this paper draws focus on (i) the South African health care system, (ii) diabetes in South Africa, (iii) policy and intervention strategies, and (iv) modelling techniques and approaches that could be utilised to model and subsequently evaluate complex systems. At the onset of the paper, an analysis of the South African health care system is presented to provide context for this paper, wherein the efficiency of the system, as well as the inequality between the public and private health care system and increased burden of disease, are discussed. The paper then focuses on specific aspects of diabetes in South Africa, such as the disease itself and the growing prevalence within the country, after which a discussion of the financial implications and management of the diabetes within South Africa highlights the need to address diabetes from the perspective of diabetic management intervention strategies.

The focus of this paper then shifts to a discussion of the approach used during policy analysis. An analysis of South African diabetic policy and intervention strategies is then presented, together with requirement specifications developed as an outcome of this analysis. These requirement specifications develop a need for a specific modelling technique, given the context, to analyse policy interventions. Thereafter, this paper introduces the concept of simulation modelling, where appropriate modelling approaches are discussed and evaluated so as to determine which approach most comprehensively meets the needs of the requirement specifications. Finally, this paper motivates the need to consider alternative intervention strategies for the management of diabetic policy formulation in South Africa by drawing on key points discussed throughout the paper.

2. SOUTH AFRICAN HEALTH CARE SYSTEM

During the past two decades, the South African government has aimed to improve the condition of the public health care system by outlining a clear model with a focus on primary health care (PHC) [5]. PHC, in the case of South Africa, refers to the first line of health care that a patient receives, at either a clinic, community health centre or district hospital, which may include the treatment of a disease, referral to more specialised care if required, and prevention through health education aimed at individuals, families, and communities [6]. The inadequacy of PHC available to the majority of the South African population during the apartheid era, however, led to a significant disproportionate excess of serious health problems and challenges, which was manifested in higher infant mortality rates, as well as lower life expectancies [5]. While the post-apartheid government has since developed a primary-centred health care model aimed at all South Africans, the quality of PHC in South Africa remains challenge-stricken [5].

In order to comprehend the current state of the South African health care system, it is necessary to investigate the efficiency of the system to provide health care for the South African public. Furthermore, the inequality between private and public health care, and the increased burden of disease experienced in South Africa, needs to be analysed to develop context for this paper, and is discussed in the sections below.

2.1 Efficiency of the health care system

In 2014, *The Economist* reported on a study that performed a 166-country health outcome report comparing the health care performance and spending patterns of various countries [7]. Figure 1 displays a plot that ranks the health outcomes of a country versus the ranking on healthcare spending for each country. The outcome measure was a combined function of (i) adult mortality in 2012, (ii) life expectancy at 60 years of age, (iii) disability-

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adjusted life years, and (iv) health-adjusted life expectancy. This study found that health outcomes were directly correlated with healthcare spending [7]. According to the study, a country with a high ranking for healthcare spending should be expected to have a high ranking for healthcare outcomes. It is, therefore, contradicting to this trend that while South Africa ranks high in terms of spending, it is ranked significantly low in terms of healthcare outcomes.

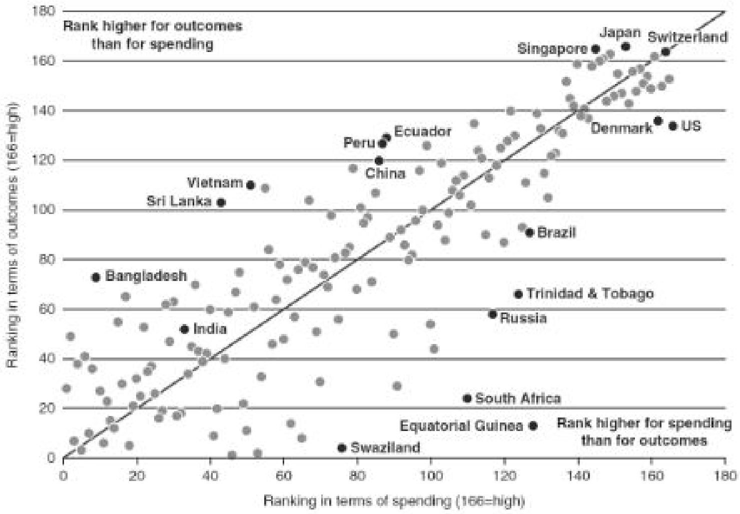

Figure 1: Health outcomes rank versus spending rank by country [7]

This result is echoed by the *Future Health Index* study, commissioned by Dutch technology company, Philips, which examined the current realities of how well the healthcare system of a country is set up for the future in order to quantify the readiness of health systems [7]. The results of the study ranked South Africa last among 19 nations in a global survey which measured healthcare system efficiency — the ability to deliver maximum results at the lowest possible cost. The study included countries such as China, France, the United States, Argentina, United Arab Emirates and Brazil, and whereas the group scored an average efficiency score of 10.5, South Africa achieved an efficiency score of 4.4 [7].

Maillacheruvu [5] argues that the quality of PHC in South Africa is challenged by two major issues: the inequality between private and public health care, and the increased burden of disease experienced in South Africa. Maillacheruvu [5] further argues that by addressing these issues, the health care outcomes of South Africa may be significantly improved. It is suggested that the inequality between public and private health care, as well as the increased burden of disease, is augmented by the historical struggles induced by the economic, political, and societal structure of the apartheid era [5]. These two issues are addressed in the respective sections to follow.

2.2 Inequality between private and public health care

Health care in South Africa varies from the most basic PHC offered by the state, to highly specialised health services available in the both public and private sector [8]. In 2015, the total health expenditure (THE) per capita was USD 570, where the THE formed 8.9% of the South African GDP [9]. According to the National Treasury's Fiscal Review [10], the South African GDP spent on health was split between the private health sector (48.5%) and the public sector (49.2%). The remaining 2.3% was donated and spent by NGOs. While the private and public sector both receive a similar share of the GDP for healthcare, the private healthcare sector only services an estimated 16% of the population, while the remaining 84% of the population relies on public healthcare services [10, 9].

In addition to the disparate patient populations between private and public health care, the number of health care providers within each system is also disproportionate. The World Health Organization estimates that only 30% of all South African physicians work in the public sector, despite the public health care sector serving 80% of the population [11]. The relatively lower number of health care providers, along with the increased number of patients in the public health care system, results in an overburdened public care system, when compared to the private sector. It is also argued that public health care workers are, in turn, overworked and thus, making it challenging to provide the same level of personalised services when compared to the private sector [12]. This

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is clearly evident in a study conducted at Tafelsig Clinic by Maillacheruvu [5], where clinicians were often overworked, and were unable to provide the health care needed to serve all the patient present at the clinic [5].

In addition to the disproportionate number of health care workers in the public and private health care sectors, the economic divide between the rich and the poor, also contributes to the persisting inequality between the two health care sectors. To further illustrate the extent of the inequality, it was reported in 2007 that South Africa had the world's 10th highest Gini index at 0.578, which is a measure of income inequity among a nation's population [13]. The economic divide in South Africa has created a separation within the national health care system, and, as a result, has developed a considerable discrepancy between the resources used by public health care and the private sector.

Another consequence of the economic divide between public and private health care is the poor usage of the health care referral system [14]. Referrals between public clinics, community health care clinics and district hospitals are standard practice [15]. The referral system begins at PHC clinics as the first step in the provision of health care [7]. If the clinic cannot assist, the patient will be referred to a community health center, as the second step in the referral system. The third step in the provision of health care is the district hospital. Thereafter, patients may be referred to secondary, tertiary, or quaternary level of care [7]. It was, however, noted by Mojaki [14] during a study conducted at the Dr JS Moroka District Hospital in the Free State, that the majority of patients seen in the outpatient department and casualty had bypassed the referral system by means of self-referral. More than 50% of these patients could have been managed at PHC clinics or community health centers, which is similar to study findings of Rutkove [16] at King Edward VIII Hospital in Durban. Long waiting times (close to 6 hours) in the hospital may have been reduced if patients were managed at their nearest PHC facility.

Mojaki [14] found that the primary reason for patients bypassing PHC facilities was their perception of the superior care and resource availability at hospitals. This perception may be rooted in the inadequacy of PHC available to non-white South Africans during the apartheid era. Other cited reasons included dysfunctional community health centers and lack of education about the referral system among patients and health professionals. In addition, less than 2% of patients were educated on the referral system, and none had been charged the bypass fees, despite a provincial policy. Mojaki [14] argues that the tendency of patients to bypass PHC facilities disrupts hospital's core functions and is linked to the overcrowded outpatient department in these hospitals.

It may, therefore, be seen from the studies at Tafelsig clinic and Dr JS Moroka Hospital, together with the plethora of other health care facilities facing almost identical situations throughout South Africa, that the overburdened public health care facilities have an insufficient number of health care providers needed to fulfil the personal, community-based values of the PHC model outlined in the National Health Bill.

2.3 Increased burden of disease

Along with the economic divide investigated in the previous section, another defining characteristic of the public PHC system of South Africa is the considerable array of long-term diseases that providers must treat. This, in turn, minimises the available time allocated to other aspects of PHC, which includes counselling and prevention through education [5]. Communicable diseases, such as HIV/AIDS and Tuberculosis (TB) are widespread in South Africa, but non-communicable diseases, including hypertension and diabetes, are growing in prevalence [17]. With more chronically-ill patients, public PHC facilities are under significant strain to dedicate sufficient resources to assist all patients.

The most considerable health problem that South Africa faces is the combined HIV and TB infection rate [18]. In 2011, the prevalence of HIV among South Africans aged 15-49 years was 17.3%, which is among the highest in the world [18], and, in 2014, TB was the leading cause of death in South Africa [18]. Additionally, individuals affected by HIV/AIDS are more susceptible to other infections, such as TB, due to their compromised immune systems. In fact, individuals who are HIV positive are ten times more likely to develop TB [19]. Treatment methods for TB exist and are readily available, but require a strict treatment regimen that may last up to six months, and may necessitate multiple visits to a clinic per week [19]. The prolonged period required to treat TB increases the burden of communicable diseases on PHC facilities, and also decreases the likelihood that patients will complete their recommended course of treatment [18].

Statistics South Africa [20] recently released a report on the top ten leading causes of death in South Africa, based on all death notification forms maintained by the Department of Home Affairs. Although South Africa is afflicted with a high HIV and TB rate, the data, provided by Statistics South Africa, found that 55.5% of all deaths were attributed to non-communicable diseases and that diabetes was the second leading cause of death in 2015 after TB [8]. Furthermore, it has been reported that diabetes is the number one killer of women living in the Western Cape Province [21]. Potential associations between diabetes and TB, as well as HIV, may also further complicate the pattern of increasing diabetes prevalence in South Africa and the challenges posed on resource-constrained health systems. A recent meta-analysis of thirteen studies found that individuals with diabetes were associated with a three-time elevated risk of tuberculosis [22]. Furthermore, the high prevalence of HIV, as well as antiretroviral therapy treatment for HIV, may increase the prevalence of diabetes risk factors and, consequently, diabetes incidence [5].

Although once regarded predominantly as a disease related to the developed world, it is clear that diabetes now exerts a significant burden in South Africa, which is expected to increase [4]. Many diabetic patients face significant challenges accessing diagnosis and treatment, further contributing to the high mortality and prevalence of complications observed [1].

3. DIABETES IN SOUTH AFRICA

Global projections by the International Diabetes Federation (IDF) has shown that diabetes prevalence is expected to double from 285 million in 2010 to 592 million in 2035, with the sub-Saharan African region bearing the burden of this increase, and South Africa at the forefront [24]. Of the 14.7 million people living with diabetes in Africa [2, 3], approximately 11 million are found in sub-Saharan Africa, and 2.3 million in South Africa. Until recently, diabetes was considered uncommon in these regions, but due to demographic and lifestyle changes, diabetes is increasingly identified as a prevalent health problem [25].

This section firstly provides a brief overview of the diabetes disease. Thereafter, the prevalence of diabetes in South Africa will be explored. Consequently, the increasing financial implications of the disease is discussed. Finally, the section concludes with an analysis of the management of diabetes in South Africa.

3.1 The diabetes disease

Diabetes mellitus[4], or diabetes, is a chronic and lifelong condition which may affect the human body's ability to use the energy from ingested food. There are three major types of diabetes[5]: type 1 diabetes, type 2 diabetes, and gestational diabetes [3, 26].

3.2 Diabetes prevalence in South Africa

Type 2 diabetes accounts for 90% of diabetes cases in sub-Saharan Africa, whilst type 1 diabetes and gestational diabetes constitute the remaining 10% [4]. The prevalence of type 2 diabetes has increased significantly from that recorded in pre-1985 surveys conducted within the region. These surveys found that the prevalence for diabetes in sub-Saharan Africa was typically below 1%, with the exception of studies in South Africa, where a 3.6% prevalence was observed [4].

Data from the IDF [2] estimates that, as of 2018, 7% of South Africans between the ages of 21 and 79 years have diabetes. Based on population estimates for South Africa, it is estimated that 2.29 million South Africans in the aforementioned age group have diabetes [6]. Of the 2.29 million people with diabetes, 1.4 million (61.1%) are undiagnosed [26]. Furthermore, it is estimated that an additional 5 million South Africans have pre-diabetes; a condition most likely caused by insulin resistance and results in blood glucose levels being higher than normal, but not significantly high enough to be classified as type 2 diabetes [3]. The highest prevalence of diabetes in South Africa is among the Indian population, with a prevalence of 11-13% [3]. This is followed by 8-10% in the coloured community, 5-8% among the black community, and 4% among the white community [3].

As diabetic symptoms may initially be extremely mild and develop gradually, combined with an ineffective PHC education intervention system in South Africa, many people fail to recognise symptoms as warning signs of diabetes [3]. In most cases, diabetic complications may have been avoided entirely by early diagnosis and proper treatment [3]. Due to the already considerable burden of disease in South Africa, however, the growing prevalence of diabetes may potentially be unavoidable and lead to increased strain on the already stressed health care system, as well as economic ramifications for South Africa.

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[4] A variable disorder of carbohydrate metabolism caused by a combination of hereditary and environmental factors and is typically characterised by an insufficient secretion or utilisation of insulin, excessive urine production, significant amounts of sugar in the blood and urine, and by thirst, hunger, and loss of weight [3]. A number of medical risks are associated with diabetes, such as diabetic retinopathy, diabetic neuropathy, and diabetic nephropathy [26]. Furthermore, persons with diabetes have an increased risk of heart disease and stroke [26]. Treatment is required to maintain blood sugar levels within a target range, and includes taking several insulin injections every day or using an insulin pump, monitoring blood sugar levels and eating a healthy diet that spreads carbohydrate throughout the day [26].

[5] Type 1 diabetes is referred to as "insulin-dependent" diabetes and typically emerges during childhood. This variation of diabetes is an autoimmune condition, where the human body attacks its own pancreas with antibodies. After significant damage, the pancreas of a person with type 1 diabetes is be unable to produce insulin [4]. The most common form of diabetes is type 2 diabetes and accounts for 95% of diabetes cases in adults [3]. With the rise of obesity in children, however, type 2 diabetes is now being increasingly diagnosed in young people and teenagers [29]. In the case of type 2 diabetes, the pancreas is typically capable of producing some insulin. The insulin is, however, either insufficient for the needs of the body, or the cells of the body are resistant to the insulin. The final variation of diabetes is triggered by pregnancy, which is referred to as gestational diabetes, and occurs between 2% to 10% of pregnancies [26]. In contrast to type 1 and 2 diabetes, gestational diabetes typically resolves itself after pregnancy.

3.3 Economic implications of diabetes in South Africa

In 2010, the cost per person with diabetes in South Africa per annum was approximated by the Centre for Diabetes and Endocrinology (CDE) as USD 405.52 [28]. The Society for Endocrinology, Metabolism and Diabetes of South Africa (SEMDSA) estimated that the cost per person with diabetes in South Africa per annum in 2015 increased to USD 918.9 [28]. This is consistent with the observed increased prevalence of diabetes in South Africa. As discussed in section 2.2, the healthcare spending per capita was equivalent to USD 570, which is significantly lower than the cost per person with diabetes in South Africa estimated by SEMDSA.

Furthermore, the estimated cost per diabetic person in South Africa is likely to be significantly lower than the actual cost, due to factors such as undiagnoses, the cost for diabetes prevention programs, over-the-counter medications required for diabetes-related eye and dental problems, and the cost of reduced quality of life, pain and suffering which cannot be measured directly [29]. The economic implications further extend to the public health care system, which may continue to be over burded by the potencial increase of diabetcis to treat. With the increasing impact of diabetes that is expected to occur, future health care spending for diabetes is likely to increase.

3.4 Management of diabetes in South Africa

In order to address the increasing financial and economic strain of diabetes in South Africa, the management of the disease needs to be considered. In South Africa, there are a number of private and public agencies, with a wide spectrum of strategies, in attempt to manage diabetes.

In the private sector diabetes landscape, there exists the CDE - a diabetes management solutions enterprise in South Africa [28]. Their mandate is to improve the health and lives of diabetics by means of various formal diabetes management programmes, partnerships with medical aid schemes, and the education and accreditation of healthcare professionals in diabetes care principles [28]. Additionally, a non-profit organisation, Diabetes South Africa (DSA), which was founded to be a support and advocate for all people living with diabetes in South Africa [30]. The DSA primarily acts as an advocate for diabetics in South Africa by lobbying for better facilities, cheaper medication and better health care services, as well as promoting prevention through public awareness of diabetes, and its symptoms and risks [30].

While a plethora of private agencies play a role in the management of diabetes in South Africa, the most prominent is agency is SEMDSA – a scientific society that aims to further the clinical practice, as well as promote both clinical and scientific research and publication, into all branches of endocrinology, metabolism and diabetes [26]. This society strives to promote acceptable standards for training and the professional practice of endocrinology, metabolism and diabetes as well as to provide advice, where necessary, regarding the academic standard of individuals and training units [26]. SEMDSA also aims to promote access to the provision of health care services and adequate treatment for all affected diseases related to endocrinology, metabolism and diabetes, with particular focus on the poor and needy [26]. In 2017, SEMSDA released the *SEMDSA 2017 Guidelines for the Management of Type 2 diabetes mellitus* diabetic guideline to inform general patterns of care, to enhance diabetes prevention efforts and to reduce the burden of diabetes complications in people living with this disease, which is based on international best-practice [26]. The guideline addresses diabetes diagnosis, screening, diabetic lifestyle interventions, glucose management, comorbidities and complications, as well as focusing on special diabetic populations, such as children, adolescents, older persons, pregnant women [26]. It is, however, noted that this guideline only pertains to the care of adults with type 2 diabetes at primary care level [26].

In 2014, SEMDSA collaborated with the South African Department of Health (DoH) to produce the updated *Management of type 2 diabetes in adults at primary care level* policy guideline to manage diabetes from a public healthcare sector perspective [31]. The aim of implementing the updated guideline was to reduce diabetic complications, as well as to reduce premature mortality from diabetes. This formed an integral part of the Diabetes Implementation Strategy for South Africa, which was developed in response to the African Diabetes Declaration and Strategy of 2006 [31]. In this policy guideline, diabetes diagnosis, screening, glucose management, comorbidities and complications are addressed [31]. The policy, however, fails to address the treatment of diabetes at a level higher than PHC, or diabetic treatment for children.

In the 2013 *Strategic Plan for the Prevention and Control of Non-Communicable Diseases 2013 – 2017*, a listing of all the health care policies published by the DoH since 1998 are presented [32]. Prior to the 2014 *Management of type 2 diabetes in adults at primary care level* policy, only two other diabetic guidelines are listed – the 2005 *Management of diabetes type 1 and type 2 in adults at hospital level* and the 2008 *Guidelines for the management of type 1 diabetes in children* [32]. These two guidelines are, however, not publicly available. Kleinert [33] suggests that the content of South African health policy, as well as the poor documentation and availability thereof, is hampered by ineffective leadership, inexperienced and unaccountable managers, and a weak health system. In addition, both the 2005 *Management of diabetes type 1 and type 2 in adults at hospital level* and the 2008 *Guidelines for the management of type 1 diabetes in children* are only implemented as guidelines, as opposed to policy [32]. The 2014 *Management of type 2 diabetes in adults at primary care level*

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policy is, therefore, the most recent, publicly available diabetic policy implemented by the DoH at a national level and will be useful when considering the need to investigate alternative policies and intervention strategies to manage diabetes in South Africa. In addition, the *SEMDSA 2017 Guidelines for the Management of Type 2 diabetes mellitus,* while not published by the DoH, may prove to be useful in understanding the management of diabetes, as it is the most recently published diabetic guideline in South Africa [26].

In order to manage diabetes effectively in South Africa, the public health system should ensure that implemented intervention strategies and policies address the needs of diabetics at *all* levels of health care. This paper, therefore, argues that there is substantial need to investigate alternative policy and intervention strategies to inform diabetic policy formulation in South Africa.

4. POLICY AND INTERVENTION STATEGIES

According to Walt [34, 35], policy analysis is a multi-disciplinary approach to public policy, which aims to explain the interaction between the interests and ideas of the various stakeholders in the policy process, and may be useful a useful tool in understanding past policy failures and successes and planning future policy implementation.

As discussed in Section 3.4, it is crucial that policy and intervention strategies are developed, evaluated and implemented that ensures effective management of diabetic health care in South Africa. To further highlight this need, the methods of health policy analysis, as well as a brief overview of South African diabetic policy and intervention strategies, are discussed in the sections to follow.

4.1 Policy analysis approach

Walt [35] argues that health policy analysis typically focuses on the content of policy reform and neglects the actors involved in the reform, the processes required to develop and implement change, and the context within which the policy is developed. When a disproportionate amount of focus is placed on the content of a policy, attention is typically diverted away from understanding the processes, which substantiates why desired policy outcomes may fail to emerge [35]. Reich [36] argues that policy reform is generally a political process, which affects the inception, formulation and implementation of policy. Furthermore, policy-makers, whether politicians or bureaucrats, are acutely aware that reforms are often unpopular and may cause significant social instability [35].

From a policy-domain characterised primarily by consensus, health policy is increasingly subject to conflict and uncertainty. This encouraged Walt [35] to generate alternative ways of analysing policy. Walt argues that policy analysis from a systems perspective offers a more comprehensive framework for thinking about health reform, than approaches which concentrate on the technical features of the content of reform. Walt, therefore, suggests the use a simple analytical model, as shown in Figure 2, to conduct policy analysis. This model, commonly referred to as the policy analysis triangle, incorporates the concepts of context, process, content, and actors to allow policy-makers and researchers to understand the process of health policy reform better, and to plan for a more effective implementation.

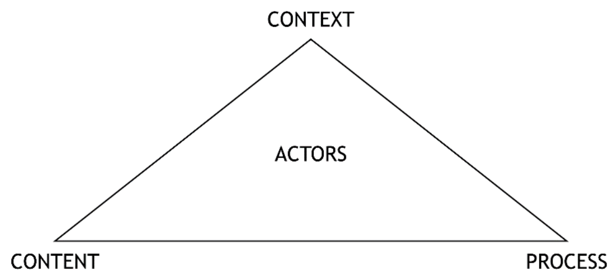

Figure 2: Policy analysis triangle [35]

The policy analysis triangle is a simplified model of a complex set of interrelationships. This model also considers the system as a whole, as opposed to each entity separately. This rationale may be observed as follows: *actors*, as individuals, members of interest groups, or professional associations, are influenced by the *context* within which they live and work. Context may be affected by many factors, such as instability or uncertainty created by changes in political regime, the economic standpoint of a country, social inequalities, historical experiences, or culture. The *process* of policy-making is in turn affected by actors, their position in power structures, their own values, and expectations of the policy. The *content* of policy may, therefore, reflect some or all of the above dimensions.

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The traditional analysis focus on the content of policy, but neglects the other dimensions of process, actors and context, which may significantly affect the successful implementation of a policy [35]. In adopting the model, this paper argues that policy is not developed free of bias, but is rather the outcome of complex social, political and economic interactions, as well as non-interactions.

4.2 Analysis of South African diabetic policy and intervention strategies

As discussed in Section 3.4, two South African policy guidelines were identified to be in most prominant in managing diabetes in South Africa. The first of which is the *SEMDSA 2017 Guidelines for the Management of Type 2 diabetes mellitus* diabetic guideline — published by SEMDSA, a private organisation. The second is the 2014 *Management of type 2 diabetes in adults at primary care level* policy guideline — published by the South African Department of Health (DoH), a government entity. In order to understand these policy guidelines, a policy analysis is simultaneously conducted on both policies using the policy analysis triangle introduced in Section 4.1.

The policy analysis begins by considering the *actors* involved in both policies. In the context of the public policy of South Africa, it is observed that the policy was developed by the South African DoH with advice and direction provided by the SEMDSA Steering Committee and the Advisory Committee [26]. It is, however, noted that while these *actors* (the DoH and subject-matter experts) were acknowledged for their contribution to the policy, the consultation of diabetic patients, PHC clinicians, and community health workers were not mentioned. Public policy is, however, typically created in an open environment with free debate is subject to the force of law, whereas private organisations may develop their own policy based on the rules and regulations of their organisation without public accountability. This characteristic of private policy should to be considered when analysing the SEMDSA policy. While the *content* of the SEMDSA is based on international best-practice and the *actors* involved include the guideline committee (consisting of an extensive number of subject-matter experts), the public was not acknowledged as *actors* in this policy. Since there were, however, a significant number of subject-matter experts involved in the creation of both policies, as well as an external moderation process, the *content* of both policies may, therefore, be considered of a significantly high quality that meets international best-practice. It is, however, viewed that the *content* of both policies is directed at adults with type 2 diabetes at primary care level, and do not address higher levels of health care, or other types of diabetes.

While analysing the *actors* involved, it is seen that diabetic patients, PHC clinicians, or community health workers were not actively involved in the policy-making process. The knowledge of the involvement of actors is vital when the *context* of a policy is considered. As described in Section 2.2 and 2.3, there is a large inequality between the private and public sector, and an increased burden of disease in South Africa, respectively. This has placed a significant stress on the PHC clinicians and community health workers, and, therefore, increases the difficulty of diabetics assessing sufficient health care. In addition, the poor usage of the referral system in South Africa, as discussed in Section 2.3, is extensively relied on in the public policy. Although the *content* of both policies should equip PHC clinicians to treat diabetics effectively, the *context* of the current South African health care system prevents PHC clinicians from providing sufficient health care to diabetics. Finally, the *process* aspect of the policy analysis is considered. While the South African DoH released and implemented the *Management of type 2 diabetes in adults at primary care level* policy guideline in 2014 to manage diabetes in South Africa, the prevalence of the disease has significantly increased, as discussed in Section 3.2. This may be similarly found for the policy released by SEMDSA.

From the above policy analysis, the following requirement specifications may be developed to investigate alternative intervention strategies for the management of diabetic policy formulation in South Africa by means of a modelling approach:

i. **Problem identification**: Does the modelling technique assist the developer in identifying the intervention strategies and actors within the entire system?

ii. **Non-linear and dynamic intereactions:** Does the modelling technique accurately investigate the effect of intervention strategies on the healh care system?

iii. **Flexibility**: Does the model adapt well to varied input data and changes to interrelationships?

iv. **Outcome accuracy**: Do the results of the model justify the computational intensity?

v. **Indication of effect over time**: Does the model provide the expected outcome of the system over a time period specified in order to model future predictions?

These requirement specifications may, therefore, be utilised in identifying an appropriate modelling approach to investigate alternative intervention strategies for the management of diabetic policy formulation in South Africa.

5. THEORETICAL MODELLING OF DIABETIC INTERVENTION STRATEGIES IN THE SOUTH AFRICAN HEALTH CARE SYSTEM

Complex, dynamic systems typically presents multiple non-linear interactions, and may, therefore, also act as barriers to solving problems by means of analytical approaches. In order to address the issues that arise in complex systems, Banks [37] recommend that a mathematical computational method, based on iterative algorithms, should be employed, and identified simulation as the most appropriate method to analyse and understand such systems. Additionally, Banks [37], as well as Borshchev [38], noted that the use of simulation allows for the behaviour of a system to be evaluated and predicted beyond that of the available data for time or space. According to Banks and Borshchev, simulation is the only practical means to test complex system models, and suggest that without simulation, even the best conceptual models may only be tested and improved by relaying on the learning feedback through the real-world. This real-world feedback is, however, slow and often rendered ineffective by dynamic complexity, time delay, inadequate or ambiguous feedback, poor reasoning skills, or the cost of experimentation [37, 38]. In these circumstances, simulation becomes the only reliable way to test hypotheses and evaluate the likely effects of interventions, such as policy.

In the section to follow, simulation modelling approaches will be introduced and discussed. Thereafter, the simulation modelling methods will each be evaluted, based on their ability to meet the requirement specification developed in Section 4.2, in order to identify an appropriate modelling approach to investigate alternative intervention strategies for the management of diabetic policy formulation in South Africa.

5.1 Simulation modelling approaches

According to Borschev [38], the three most commonly used simulation modelling approaches are system dynamics modelling, agent-based modelling, and discrete-event modelling.

System dynamics is a simulation method, which was first developed in the 1950s by MIT Professor, Jay Forrester, to examine and characterise the dynamics of economic, as well as social structures [38, 39]. It is suggested by Borshchev [38], that when using a system dynamics approach, that the most important notion is to maintain a point of view from within the system, and that it should, therefore, be viewed as endogenous. This view is achieved by modelling the system as a casually closed structure which, in turn, defines the system's behaviour [38, 40]. The next step is to identify the various feedback loops. Feedback loops can be thought of as circular causality in that they essentially continually recalibrate the system based on the state of other parts within the structure [38]. Feedback loops are considered the crux of systems dynamics. It is suggested that all the concepts in the real system should be defined as continuous quantities, interconnected in loops of information feedback and circular causality. Furthermore, the system dynamics approach involves identifying the different accumulations, or stocks within the system, as well as the flows that affect them [38].

Agent-based modelling is a modelling approach developed in the early 2000s as a result of the rapid growth of available CPU power and memory. This is in the light of the fact that agent-based models are more computationally demanding of both when compared to system dynamics and discrete event models [37, 38]. In agent-based modelling, a system is modelled as a collection of independent decision-making entities, called *agents* [38]. In this modelling method, each individual agent assesses its situation and executes various decisions or actions based on a set of established rules [38]. Borshchev [38] suggests that agent-based modelling is ideal when the simulation developer possesses insight into how the objects in the system behave individually, rather than knowing how the system behaves as a whole. The model may, therefore, be constructed using the bottom-up modelling approach, commencing by identifying objects or agents and defining their behaviours. This modelling method differs from the systems dynamics approach, which develops a model through means of a top-down modelling approach [38].

Discrete-event systems are systems where specific state changes or events occur at discrete instances in time and that no state change takes place in the system between these events. Systems that are defined by occurrences discrete events may be modelled using *discrete event modelling* [38]. According to Borshchev [38], the level of abstraction suggested for discrete event modelling is significantly lower than that of system dynamics modelling. Abstraction refers to the complexity by which a system is observed [38], and is an important consideration depending on the type of problem at hand. The highest level of abstraction considers the entire system in low detail, whereas the lower levels of abstraction normally investigate smaller system components in a higher level of detail. In discrete event modelling, each object in the system is represented by an entity or a resource unit at a low level of abstraction, whereas the individual objects in a system dynamic model are aggregated, and are therefore modelled as a high abstraction [38].

5.2 Evaluation of simulation modelling approaches

When considering which simulation modelling method is most appropriate to understand the influencing factors of various diabetic intervention strategies for the management of diabetic policy formulation in South Africa, the decision is primarily based on the type of system being modelled and the purpose of this system [38]. Borshchev [38], however, also notes that the selection of a modelling approach is often largely influenced by the skill set or background of the simulation developer. Another consideration when selecting the modelling approach may be the level of *abstraction*.

In order to select the most appropriate modelling approach, discrete-event modelling, system dynamics modelling, and agent-based modelling will each be evaluated based on the ability of the approach to meet the requirement specifications developed in Section 4.2. As the selection of a modelling approach is often largely influenced by the skill set or background of the simulation developer, 'ease of creation' is added as an additional requirement specification. Table 1 contains a summarised description of the three modelling approaches and their capacity to meet the requirement specifications.

Table 1: Summary of simulation modelling techniques [37, 38, 39, 40]

Attributes	Modelling approaches		
	Discrete-event	**System dynamics**	**Agent-based**
Problem identification	Very poor	Excellent	Poor
Non-linear and dynamic intereactions	Very good	Very good	Excellent
Flexibility	Very good	Very good	Very good
Outcome accuracy	Poor	Excellent	Good
Indication of effect over time	Very good	Very good	Very good
Ease of creation	Poor	Good	Very poor

Discrete-event modelling is found to be an inadequate approach for the intended modelling purposes, as this approach is better suited to model queuing systems and supply chains [38], whereas the intervention strategies for a diabetic health care system may be viewed as a continuous flow of resources and information. Furthermore, the discrete-event approach is typically focused on the on the details of a system rather than from a holistic system perspective [38], and may, therefore, be unable to identify the effects of the various intervention strategies on the system. This may not be ideal in the context of national health care, as the problem is almost always viewed at a high-level perspective. An additional shortfall of the discrete-event approach is that ease of model creation is poor [38].

System dynamics modelling, and agent-based modeling are identified the most appropriate modelling techniques to understand the effects of various intervention strategies to manage diabetic policy formulation given the requirement specifications, as summarised in Table 1. Agent-based modelling is, however, rejected for the purposes of this study, as this approach is better suited to model a system at a low level of abstraction [37, 38]. Consequently, in the case of agent-based modelling, the 'Problem identification' aspect is scored 'poor'. Although agent-based modelling is excellent at incorporating non-linearity in a system, it is significantly criticised for its poor ease of creation [37].

System dynamics modelling is, therefore, selected as the appropriate modelling approach based on the identified requirement specifications. As the South African healthcare system consists of a multitude of stakeholders, the effects of diabetic policy interventions would be more effectively modelled from a systems perspective [39, 40], therefore, scoring 'excellent' for the 'problem identification' aspect, as well as 'very good' for the 'non-linear and dynamic interactions' category. Furthermore, the system dynamics approach adapts well to varied input data and changes to interrelations, and also has the capabilities to provide the expected outcome of the system over a time period specified in order to model future predictions [39, 40]. In conclusion, system dynamics modelling will also provide a more holistic solution to understand the influencing factors of various diabetic intervention strategies in the South African healthcare context for the management of policy formulation.

6. CONCLUSION

The increasing prevalence of diabetes in the world is a widespread concern. While improvements have been made in the epidemiology and management of diabetes in the developed world, the same advances have not been made in South Africa. In addition, it was noted by The Economist that while South Africa ranks high in terms of health care spending, it is ranked significantly low in terms of health care outcomes.

The ability of the South African health care system to provide sufficient PHC has been constrained by several factors, such as the increased stress on the public health system, caused by the inequality between public and private health care, and the increased burden of disease in South Africa. Communicable diseases, such as

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HIV/AIDS and TB are widespread in South Africa, but non-communicable diseases, such as diabetes, are growing in prevalence. In fact, about 7% of South Africans have diabetes, and, according to the IDF, this percentage is only expected to increase. While public and private policies have been developed to address the growing prevalence of the disease, this paper argues the importance of implementing policy and intervention strategies which address the needs of diabetics, at all levels of health care, to effectively management diabetic health care in South Africa.

When a disproportionate amount of focus is placed on the content of a policy, attention is typically diverted away from understanding the processes, context, and actors of a policy, which explains why desired policy outcomes may fail to emerge. This paper argues that policy-making should not only focus on policy content, but also policy context, processes and actors, achieved in the triangle policy analysis. By applying this analysis tool to existing South African diabetic policies, requirement specifications were developed to identify a modelling approch to investigate alternative intervention strategies for the management of diabetic policy formulation in South Africa. These requirement specifications include (i) problem identification, (ii) non-linear and dynamic interations, (iii) flexibility, (iv) outcome accuracty, and (v) indication of effect over time.

This paper argues that the South African health care system, together with diabetic policy, is a complex system, with non-linear and dynamic interactions, and the approach to analysing such a system should take the form of a simulation model. In order to select the most appropriate simulation modelling approach, three of the most commonly used simulation modelling approaches were evaluated based on their ability to meet the developed requirement specifications. System dynamics modelling was deemed the most appropriate modeling tool to provide the holistic approach to investigate the influencing factors of various diabetic intervention strategies in the South African health care context for the purpose of informing policy formulation.

In conclusion, this paper argues that there is justified need to investigate alternative intervention strategies for the management of diabetic policy formulation in South Africa, and that the most appropiate tool for investigation would be by means of a system dynmics modelling approach.

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D.2 A system dynamics approach to modelling the management of the increased prediabetic prevalence of the South African population

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A system dynamics approach to modelling the management of the increased prediabetic prevalence of the South African population

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***Abstract*—The increasing prevalence of prediabetes in South Africa is of great concern. Due to the complex nature and non-linear interactions that exist within the health care system to address prediabetic health care, a system dynamics-based approach is suggested as an appropriate analysis tool to evaluate and gain insight into the dominant factors that influence the effective management of prediabetes. This is intended to subsequently identify more effective and efficient prediabetic policy and intervention strategies. A six-dynamic hypothesis is proposed in the form of a causal loop diagram that was used in the development of a system dynamics model. In the developed system dynamics model, five interventions strategies, identified as scenarios, were tested. Finally, the increased screening of high-risk individuals for prediabetes was identified as the most effective intervention strategy for reducing the prediabetic population.**

Keywords—Prediabetes, Diabetes, System dynamics, South Africa.

I. Introduction

Diabetes Mellitus, commonly referred to as diabetes, is a growing problem throughout the world — largely caused by the increased longevity and the aging of the population, but also due to numerous changing environmental and lifestyle factors that lead to reduced physical activity and increased obesity in both developed and developing nations [1, 2]. According to predictions by the *International Diabetes Federation* (IDF), the prevalence of diabetes worldwide is expected to increase from 415 million in 2015 to 642 million in 2040 [3]. Similarly, the IDF estimates that the prevalence of diabetes has increased from 4% of the South African population in 2010 to 7% in 2018 — constituting 3.91 million South Africans based on current population estimates. Of the estimated 3.91 million South Africans with diabetes, 61.1% are undiagnosed and are unaware of their heath condition [4]. The most significant factor is, however, that an additional 5 million South Africans are estimated to have prediabetes, a condition which leads to diabetes, but is not yet classified as diabetic [5]. Furthermore, the Centre for Disease Control and Prevention has reported that only 10% of prediabetic are diagnosed [6].

In order to highlight the need to manage the increased prediabetic prevalence of the South African population, this paper draws focus on the (i) different variations and clinical stages of the diabetes disease, as well as the (ii) management of diabetes within the context of the South African healthcare system. Furthermore, these two areas of focus assist in determining an appropriate methodology approach to investigate alternative intervention strategies to more effectively manage the increased prediabetic prevalence of the South African population. Thereafter, the methodology approach is applied to the specific case of prediabetes in South Africa to determine intervention strategies that are effective in managing the increased prediabetic prevalence of the South African population. Finally, the results of the scenario analysis are presented as closing policy recommendations.

II. Existing Theories and Previous Work

This section briefly introduces the variations together with the clinical stages of the diabetes disease. Thereafter, diabetes, as well as the management thereof, is described within a South African health care context.

A. *The diabetes disease*

Diabetes is a chronic and lifelong condition which may affect the human body's ability to use the energy from ingested food. There are three major types of diabetes: Type 1 diabetes, type 2 diabetes, and gestational diabetes [7].

Type 1 diabetes typically emerges during childhood and arises from the human body attacking its own pancreas with antibodies. After significant damage, the pancreas of a person with type 1 diabetes is unable to produce insulin [8]. Type 2 diabetes is the most common form of diabetes and accounts for 95% of diabetic cases in adults [2]. Type 2 diabetes is increasingly being diagnosed in young people and teenagers due to the rise of obesity in children [9]. In this case, the insulin in a person's body is either insufficient for the needs of the body, or the cells of the body are resistant to the insulin. The third most notable variation of diabetes is triggered by pregnancy and is referred to as gestational diabetes. This form of diabetes only occurs between 2% to 10% of pregnancies

[7], and, in contrast to type 1 and 2 diabetes, gestational diabetes typically resolves itself after pregnancy. Other less notable forms of diabetes, such as maturity onset diabetes of the young and latent autoimmune diabetes of adulthood [10], also exist.

When the clinical stages of diabetes are considered, the spectrum of glucose intolerance (term for metabolic conditions which result in high blood glucose levels [11]) extends from normoglycaemia to intermediate hyperglycemia, and finally to diabetes [12]. A fasting plasma glucose concentration (the glucose concentration in the blood during a period of fasting [12]) of less than 6.1mmol^{-1} has been selected a 'normal' non-diabetic value or a normoglycemia state [12]. Although arbitrary, such values have been observed in people with proven normal glucose tolerance [12]. Five clinical stages of diabetes then ensue during the normoglycemia state. The first stage is pre-diabetes — a condition in which blood sugar is high, but not high enough to be type 2 diabetes — and includes individuals with a fasting glucose state of between 6.1 to 6.9 mmol^{-1} [12]. Approximately, 5 to 10% of people with pre-diabetes will progress to diabetes per year, with the same proportion converting back to normoglycemia [13]. The second stage is diabetes without complications and includes individuals with a fasting glucose state of higher than 7.0 mmol^{-1}. It is, however, important to note that once a diagnosis of diabetes is given, the patient cannot revert into a prediabetic state, but only into remission of the diabetic disease. Thereafter, the third, fourth and fifth clinical stages of diabetes include mild diabetic complications, diabetes with absolute insulin deficiency, and diabetes with serious complications, respectively [12].

As diabetic symptoms may be extremely mild and develop gradually, many people fail to recognise the symptoms as warning signs of diabetes [14]. In most cases, diabetic cases may have been avoided entirely by early diagnosis and effective treatment [12]. With different variations of diabetes, as well as the varying clinical stages of the disease, it is evident that health care strategies and interventions should be appropriately implemented to effectively manage all variations and clinical stages of the diabetes disease.

B. *Management of diabetes in South Africa*

While improvement has been made in the epidemiology and management of diabetes in the developed world [14], the same advances have not been made in South Africa. Of all persons with diabetes in South Africa, 51.9% have developed diabetic complications either in the form of heart disease, loss of vision, kidney failure or amputation of the extremities [5, 12]. With a 7% prevalence of diabetes in South Africa [3], 2.029 million diabetes have developed some form of diabetic complication, while 1.62 million diabetics live without complications. There are, however, 5 million South Africans that are in the first clinical stage of diabetes (i.e. prediabetes) [2].

While a clear strategy to better manage diabetes in South Africa would be to prevent the onset of the disease itself in a proactive strategy during the first clinical stage of diabetes (opposed to treating the disease and managing its complications in the later clinical stages of diabetes), it is, however, noted by Thomas et al. (2018) that the South African health care system faces significant burdens to achieve such a goal. These challenges include the inequality between private and public health care and the increased burden of disease experienced in South Africa [15].

In 2015, the total health expenditure formed 8.9% of the South African GDP [16]. According to the National Treasury's Fiscal Review, the South African GDP spent on health care was split between the private health care sector (48.5%) and the public health care sector (49.2%). The remaining 2.3% was allocated to, and spent by, NGOs [17]. While the private and public sector both receive equal portions share of the GDP for healthcare, the private health care sector only services an estimated 16% of the population, while the remaining 84% of the population relies on public healthcare services [4]. In addition to the disparate patient populations between private and public healthcare, the number of health care providers within each system is also disproportionate. The World Health Organization estimates that only 30% of all South African physicians work in the public sector, despite the public healthcare sector serving 80% of the population [4].

Along with the economic divide in the public and private health care system, another defining characteristic of the public primary healthcare system of South Africa is the considerable array of long-term diseases that providers must treat [4]. South Africa, similarly to the rest of the world, is experiencing an increasing prevalence of diabetes alongside other non-communicable diseases, such as heart disease. In South Africa, this chronic disease trend is, however, emergent in a region confronted with high rates of communicable diseases, such as HIV and Tuberculosis [4].

It may, therefore, be seen that the management of prediabetes in South Africa operates within a complex and burdened public health care system. In addition, the prevention and treatment of diabetes is a complex process, involving numerous role-players and stakeholders, such as government agencies, the healthcare system, communities and diabetic patients [14]. There are no quick or easy fixes for addressing the health and cost burdens of diabetes. Like other dynamically complex problems, diabetes is characterised by long delays between causes and effects, and the public health effort to address it is characterised by multiple concurrent goals that may be conflicting in nature. It is, therefore, necessary to consider diabetic health care in South Africa from a complex, system's perspective, with significant dynamic interactions. With the increasing burden of disease in South Africa, as well as limited resources and the complex, dynamic nature of the health care system, it is unsurprising that the prevalence for prediabetes in South Africa continues to increase [8, 14].

III. METHODS

In order to investigate alternative intervention strategies to more effectively manage the increased prediabetic prevalence of the South African population, an appropriate method should be identified. An investigation of appropriate methods is found at the onset of this section, followed by the presentation and application of the identified method to investigate the increased prediabetic prevalence in South Africa.

A. Method selection

Complex, dynamic systems typically presents multiple non-linear interactions, and may, therefore, also act as barriers to solving problems by means of analytical approaches. In order to address the issues that arise in complex systems, Banks [18] recommend that a mathematical computational method, based on iterative algorithms, should be employed, and identified simulation as the most appropriate method to analyse and understand such systems. Additionally, Banks [18], as well as Borshchev [19], noted that the use of simulation allows for the behaviour of a system to be evaluated and predicted beyond that of the available data for time or space. According to Borschev [19], the three most commonly used simulation modelling approaches are system dynamics modelling, agent-based modelling, and discrete-event modelling.

In order to select the most appropriate modelling approach, the three aforemention simulation modelling approached are evaluated based on the ability of the approach to meet a set of requirement specifications – which include problem identification, non-linear, and dynamic interactions. A summary of the evaluation of the three simulation modelling methods may be found in Table I [18, 19, 20, 21].

TABLE I. SUMMARY OF SIMULATION MODELLING TECHNIQUES

Requirement specifications	**Modelling approaches**		
	Discrete-event	***System dynamics***	***Agent-based***
Problem identification	Very poor	Excellent	Poor
Non-linear and dynamic intereactions	Very good	Very good	Excellent
Flexibility	Very good	Very good	Very good
Outcome accuracy	Poor	Excellent	Good
Indication of effect over time	Very good	Very good	Very good

System dynamics is, based on the evaluation outlined above, selected as the appropriate methodology approach, due to the method meeting more requirement specifications in Table I than the other methods. The system dynamics method is, therefore, used to consider the prediabetic health care in South Africa from a complex, system's perspective, to investigate alternative intervention strategies to more effectively manage the increased prediabetic prevalence of the South African population.

B. The system dyanmics method

System dynamics is a simulation modelling methodology first developed in the 1950s by Jay Forrester, who used the laws of physics to examine and characterise the dynamics of economic and social structures [21].

As the South African healthcare system consists of a multitude of stakeholders, the effects of diabetic policy interventions could be more effectively modelled from a systems perspective [20, 21], which may be achieved through system dynamics modelling. Additionally, the system dynamics approach is able to model non-linear and dynamic interactions — much like those shown to exist with the context of prediabetic health care in South Africa.

System dynamics has a wide application in health care, including the public health care system [22, 23] and in supporting public heath policy [24, 25]. Furthermore, it has also been utilised to understand diabetics population dynamics in the USA [1]. To the best knowlegde of the authors, there is, however, limited knowledge regarding system dyamics-based reseach on diabetes and prediabetes in South Africa.

A well used and well documented system dynamics methodology, developed by Sterman [21], consists of five steps: (i) problem articulation, (ii) dynamic hypothesis, (iii) model formulation, (iv) testing and validation, and (v) policy design and evaluation. Following the articulation of the problem in the previous section, this section continues Sterman's system dynamics methodology by first formulating a dynamic hypothesis of the issue in the form of a causal loop diagram (CLD) [21]. Thereafter, the development of the model then takes places in appropriate system dynamics software. This section concludes by defining the scenarios to be tested in scenario analysis. For background on system dynamics methodology and applications, see Sterman's comprehensive textbook [21].

C. Dynamic hypothesis

The six-dynamic hypothesis for the management of the increased prediabetic prevalence of the South African population is shown the CLD in Figure 1. It is important to note that the scope of this CLD only includes the first two clinical stage of diabetes (i.e. prediabetes and diabetes without complication), with a primary focus on prediabetes. The CLD consists of six feedback loops with three reinforcing and three balancing loops, namely the *Clinician effectiveness loop* (R1), the *Prediabetic awareness by clinicians loop* (R2), the *Access to health care loop* (R3), the *Diabetic prevalence loop* (B1), the *Prediabetic Awareness by Department of Public Health loop* (B2), *and the Prediabetic screening loop* (B3).

The *Clinician effectiveness feedback loop* (R1) demonstrates the effect of the workload on a health care professional's motivation to perform effective check-ups, which, in turn, reduces the number of prediabetic instances. Similarly, the *Prediabetic awareness by clinicians feedback loop* (R2) increases the education and prediabetic awareness supplied by doctors, which ultimately increases patient self-management and reduces the number of prediabetics in South Africa. In the *Access to health care loop* (R3), it may be observed that as the workload on a health care professional is decreased, the population access to healthcare is increased - with a greater number of people receiving adequate healthcare, more effective prediabetic check-ups are performed.

The *Diabetes prevalence feedback loop* (B1) demonstrates the relationship between the prediabetic and diabetic populations in South Africa. If the prediabetic population increases, the diabetic population is also increased, as prediabetes may develop into diabetes. As prediabetics become diabetic, however, the prediabetic population decreases, as diabetics cannot revert to the clinical stage of prediabetes.

The *Diabetic Awareness by Department of Public Health feedback loop* (B2) shows how a decrease in the number of prediabetics in South Africa may lead to a decreased motivation of the Department of Health to educate the public regarding lifestyle factors, which leads to more instances of unhealthy lifestyle factors and an increase in the number of prediabetics in South Africa. Similarly, the *Prediabetic screening feedback loop* (B3) shows how the decreased motivation of the Department of Health to address prediabetes leads to less screening of high-risk prediabetic candidates, which, in turn, leads to more undiagnosed diabetics, thus decreasing the prediabetic diagnoses rate. This results in less effective diabetic check-ups and an increase in the number prediabetics in South Africa.

D. Stock and flow model

For the purpose of this paper, the preliminary stock and flow model provides for the non-diabetic, prediabetic and diabetic population dynamics in South Africa, which will enable the exploration of the six-dynamic hypothesis. Figure 2 displays the basic causal structure of the system dynamics model developed in *Vensim PLE X32*. The full structure also

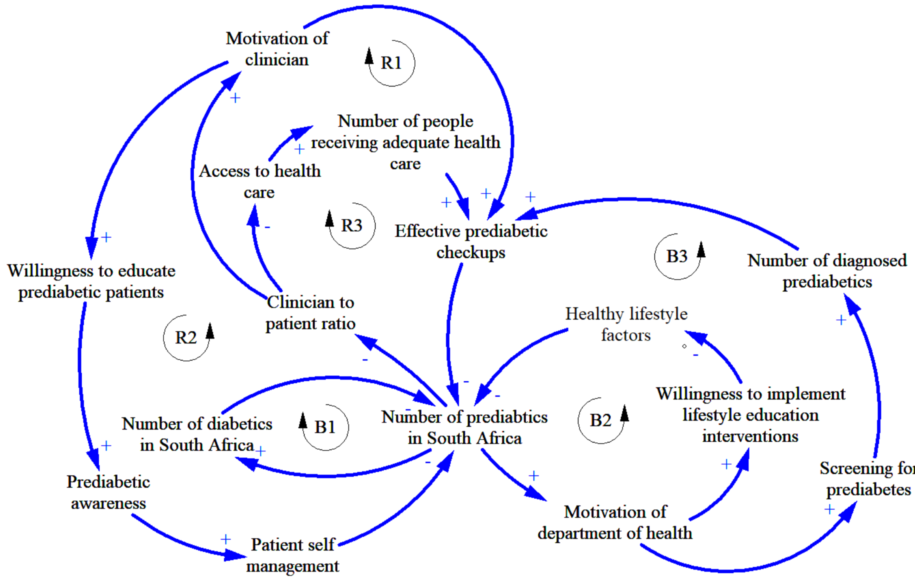

Fig. 1. Overall Management of the diabetic prevalence in South Africa CLD

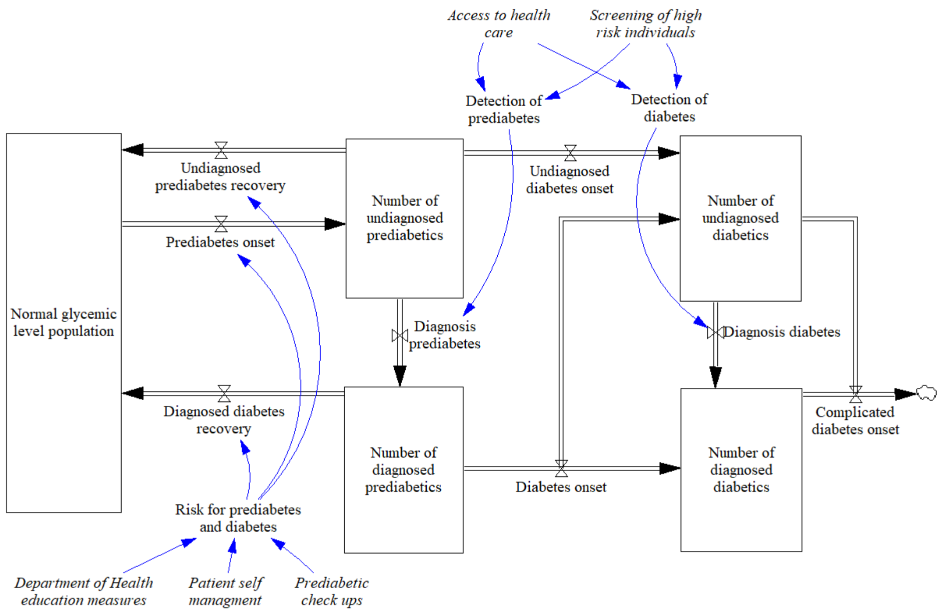

Fig. 2. Overview of model structure, showing primary population stocks (boxes) and flows (arrows with valve symbols and cloud symbols for the progression to later clinical stages of diabetes), modifiable factors affecting flows (roman), and inputs amenable to policy intervention.

includes an inflow of population growth and outflows of non–diabetes-related, prediabetic and diabetic deaths. This structure is grounded in the scientific literature on diabetes, policy, and related topics. Like all models, this one is a simplification of the real-world phenomena — details are omitted to enhance understanding and includes assumptions that are uncertain to some degree. The iterative process of developing this model continues. The model's parameters were calibrated based on historical data available for the South African adult population, as well as estimates from the scientific literature. Data pertaining to the non-diabetic, prediabetic and diabetic populations, as well as disease onset, recovery and diagnosis, were obtained from the International Diabetes Federation's diabetic report on South Africa [26].

At the core of the model is a chain of population stocks and flows portraying the movement of people into and out of the following stages: (1) normal blood glucose level, (2) prediabetes, and (3) uncomplicated diabetes. The prediabetes and diabetes stages are further divided among stocks of people whose conditions are diagnosed or undiagnosed. Diagnosis has dynamic significance, as it is necessary for proper management and control of hyperglycemia and can, in turn, greatly reduce the rates of diabetes onset, progression, and death [12].

Beyond the population stocks, Figure 2 indicates the potentially modifiable influences in the model that affect the rates of population flow, including influences that may be directly amenable to policy intervention. These flow-rate drivers include prediabetes and diabetes detection, as well as the management of prediabetes. Prediabetes and diabetes detection may be improved by two interventions: increasing the glucose screening of high-risk individuals, and those increasing access to preventive health care by addressing clinician-to-patient ratios [1]. The management of prediabetes may be improved by three interventions: encouraging patients to self-monitor glucose levels through clinician education, adopting healthy lifestyles through education, or improving the effectiveness of prediabetic check-ups [1].

E. Scenario definition

Five scenarios were developed for analysis and evaluation against the baseline results of the model and are presented in Table II.

TABLE II. SCENARIO DEFINITION

Scenario	Description
Clinician-to-patient ratio	This scenario entails increasing the current ratio of clinicians to patients by an arbitrary low, medium and high percentage from 2019 onwards to improve access to health care and treatment.
Check-up effectiveness	This scenario entails increasing the motivation of the clinician to perform an effective check-up by an arbitrary low, medium and high percentage from 2019 onwards to improve check-up effectiveness.
Lifestyle intervention education	This scenario entails increasing the education of lifestyle factors by an arbitrary low, medium and high percentage from 2019 onwards.
Self-management education	This scenario entails increasing the prediabetic self-management education an arbitrary low, medium and high percentage from 2019 onwards.
Prediabetic screening	This scenario entails increasing the screening of high-risk individuals by an arbitrary low, medium and high percentage from 2019 onwards.

As the model shown in Figure 2 was developed to demonstrate causal relationship, each scenario will be tested by increasing the scenario variable by an arbitrary low, medium and high percentage to determine the causal effects of each scenario on the reduction of the prediabetic population i.e. the management of prediabetes in South Africa. The effects of the low, medium and high percentage will also demonstrate the sensitivity of each scenario.

IV. FINDINGS

Following the development of the dynamic hypothesis and model construction, as well as the scenario definitions, in the previous section, this section begins by first presenting the baseline result of the system dynamics model. Thereafter, the results of the scenario analysis are investigated and compared against the baseline result.

A. Baseline results

The baseline results in Figure 3 show that the total number of diagnosed prediabetics continues to increase over the simulation period. This is similarly found for the number of diagnosed prediabetics, undiagnosed diabetics, and diagnosed diabetics.

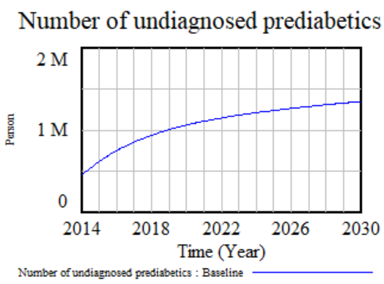

Fig. 3. Baseline results of the system dynamics model

B. Scenario results

Each scenario shown in Table II was tested in the system dynamics model by increasing the scenario variable by an arbitrary low, medium and high percentage to determine the causal effects of each scenario in the reducing the prediabetic population. A summary of the scenario results is shown in a relationship matrix (Table III), where one downwards arrow indicates an effect in reducing the prediabetic population, two downwards arrows indicate a significant effect in reducing the prediabetic population, and a rightwards-pointing arrow indicates no effect in reducing the prediabetic population.

TABLE III. SUMMARY OF SCENARIO ANALYSIS

Scenario	Scenario testing		
	Low increase	***Medium increase***	***High increase***
Clinician-to-patient ratio	↓	↓	↓↓
Check-up effectiveness	→	→	→
Lifestyle intervention education	→	→	→
Self-management education	↓	↓	↓
Prediabetic screening	↓	↓↓	↓↓

The results shown in Figure 4, 5 and 6 indicate no effect on the number of the undiagnosed prediabetic population relative to the baseline when the scenario variable of the *lifestyle intervention education* scenario (to increase the lifestyle factor education presented by the Department of Health) is increased by an arbitrary low, medium and high percentage from 2019. Similarly, an insignificant effect is

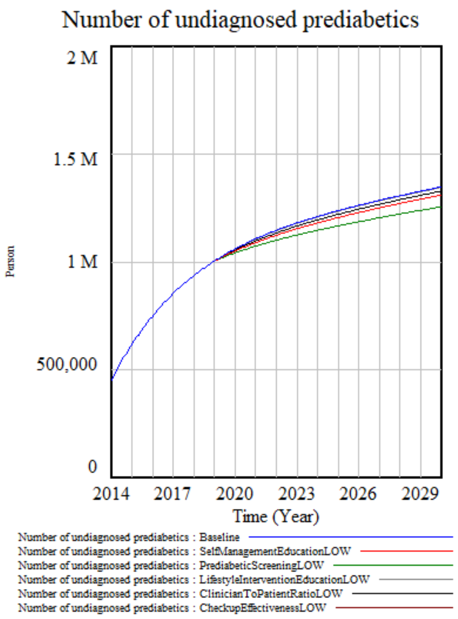

Fig. 4. Number of undiagnosed prediabetics scenario results with low variable increase

observed in the *check-up effectiveness* scenario. Possible effective intervention strategies are found in the results of the *prediabetic screening, clinician-to-patient ratio,* and *self-management education* scenarios shown in Figure 4, 5 and 6, as a reduction in the number of undiagnosed prediabetics is observed for each case. While the *lifestyle intervention education* and *check effectiveness* scenarios consistently show no effect as the scenario variable is increased by an arbitrary low, medium and high percentage, the effects in reducing the prediabetic population of the *prediabetic screening, clinician-to-patient ratio,* and *self-management education* scenarios are, however, observed to increase as the arbitrary low, medium and high percentage of each scenario variable is increased.

From the scenario results, it is postulated that an increase in the prediabetic screening can significantly improve the management of prediabetes in South Africa. This outcome is in line with Jones' [1] argument that increased screening is the most effective intervention in managing diabetes and other chronic illnesses. Furthermore, after an arbitrary medium percentage increase of the scenario variable, it is seen in Figure 5 that not only does prediabetic screening intervention reduce the prediabetic population, but also the rate of prediabetic prevalence. It is, therefore, recommended that in order to observe a significant reduction in the prediabetic population, the screening of high-risk individuals needs to be increased accordingly.

When the cost and resource allocation of each scenario intervention is, however, considered, it is noted that the screening for prediabetes is significantly resource intensive with an all-inclusive cost of $206 for each individual screening [27], whereas prediabetic self-management education in the *self-management education* scenario only requires minimal resources and financial support [12]. On the

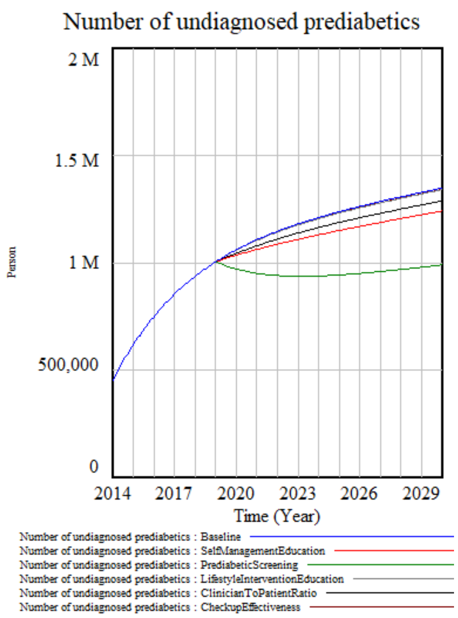

Fig. 5. Number of undiagnosed prediabetics scenario results with medium variable increase

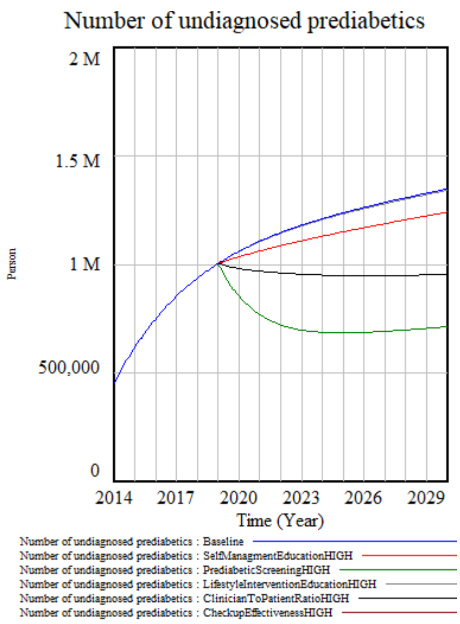

Fig. 6. Number of undiagnosed prediabetics scenario results with high variable increase

other hand, increasing the number of clinicians observed in the *clinician-to-patient ratio scenario* would be significantly resource intensive due to the clinician wages required. It is, therefore, suggested that a combination of intervention strategies be employed to identify the most effective, as well as efficient, prediabetic management strategy.

V. Conclusion

In this conclusion, the summary of the article is presented with concluding remarks. Thereafter, the limitations of the study are described. Finally, opportunities for future work of the study is discussed.

A. Summary and concluding remarks

The increasing prevalence of prediabetes in South Africa is a significant concern — involving numerous stakeholders, such as the Department of Health, the public health care system, clinicians, patients, policy-makers, and the public. It is, therefore, necessary to consider the management of prediabetes in South Africa from a holistic, systems perspective that allows for dynamic linear and non-linear interactions. System Dynamics was selected as an appropriate method to accurately capture the relevant dynamics involved in the complex management of prediabetes in the South African heath care system.

During scenario analysis, the *prediabetic screening* scenario was identified as the most effective scenario for decreasing the number of undiagnosed prediabetics. Due to the resource intensive nature of prediabetic screening, it is, however, recommended that an increased prediabetic screening intervention strategy, combined with other proven effective intervention strategies (such as self-management education, which is not resource intensive), may lead to a more effective managed prediabetic prevalence in South Africa.

B. Limitations

Perhaps the most limiting factor of the model is that the process of diabetes remission was not included. This would largely affect the diabetes without complications population, and in turn, the normal glycemic-level population. As the focus of this research was, however, to investigate the prevalence of prediabetic prevalence, only the recovery from prediabetes was included, while the remission from diabetes was excluded.

Furthermore, another limiting factor was that deaths related to the diabetes disease were modelled based on averages. In order to obtain a model more similar to the real-world system, diabetes-related deaths would need to be modelled dynamically. This limiting factor may similarly be seen where progression from diabetes without complications to diabetes with complications is modelled statically, as opposed to dynamically.

C. Future work

Further opportunities for research may include the combination of scenarios so as to determine the effect of combinations of interventions strategies on the prevalence of prediabetes in South Africa. The further investigation of prediabetic prevalence may also be largely benefited from a system dynamics model, which models the complete diabetic health care system to include diabetes with complications as an endogenous variable.

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D.3 A system dynamics approach to modelling the management of diabetes and diabetic complications in South Africa

This section contains the article "*A system dynamics approach to modelling the management of diabetes and diabetic complications in South Africa*", of which the full article citation is as follows: Thomas V, de Kock I & Bam L. (2018). "A system dynamics approach to modelling the management of diabetes and diabetic complications in South Africa." Proceedings of the *Sixth Annual System Dynamics Conference in South Africa, 22^{th}–23^{th} of November 2018, University of the Witwatersrand, Johannesburg, South Africa*, pp. 57–65.

A system dynamics approach to modelling the management of diabetes and diabetic complications in South Africa

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KEYWORDS

Diabetes, Diabetic complications, System dynamics, South Africa

INTRODUCTION

The increasing prevalence of diabetes mellitus, commonly referred to as diabetes, across the world is a global concern (International Diabetes Federation, 2017). There are three major types of diabetes: type 1 diabetes, type 2 diabetes, and gestational diabetes (Web MD, 2018). The most common form of diabetes is type 2 diabetes and accounts for 95% of diabetes cases in adults (Maillacheruvu & McDuff, 2014). Type 2 diabetes was previously seen only in middle age or older adults and was, therefore, referred to as "adult-onset" diabetes (Web MD, 2018).

Projections by the International Diabetes Federation (2017) show that, as at 2016, 415 million are living with diabetes globally. In Africa, 14.7 million people live with diabetes, of which 11 million are in sub-Saharan Africa, and 2.3 million in South Africa (Maillacheruvu & McDuff, 2014). Type 2 diabetes accounts for 90% of diabetes cases in South Africa, whilst type 1 diabetes and gestational diabetes constitute the remaining 10% (Maillacheruvu & McDuff, 2014).

Although diabetes was previously considered uncommon in South Africa, it is increasingly identified as a prevalent health problem due to demographic and lifestyle changes (Maillacheruvu & McDuff, 2014). With more chronically-ill patients, public primary health care facilities are under significant strain to dedicate sufficient resources to assist all patients. This in turn, minimises the available time allocated to other aspects of primary health care, which includes counselling and prevention through education (Maillacheruvu & McDuff, 2014). In addition, the inequality between private and public health care, together with the increased burden of disease in South Africa, prove to be significant challenges that hinder the effective management of diabetes (Maillacheruvu & McDuff, 2014). Furthermore, the prevention and treatment of diabetes is a significantly complex process, involving numerous role-players and stakeholders, such as government agencies, the healthcare system, communities and diabetic patients.

In 2014, the South African Department of Health released the *Management of type 2 diabetes in adults at primary care level* policy to manage diabetes from a public health care sector perspective (South African Department of Health, 2014). The aim of this policy was to reduce diabetic complications and premature mortality from diabetes. Despite the policy implementation in 2014, the prevalence of type 2 diabetes has, however, steadily increased from the 4.5% in 2010 to 7% in 2017 (International Diabetes Federation, 2017). In addition, the proportion of all deaths in South Africa as a result of diabetes has increased from 5.1% in 2014 to 5.5% in 2017 (Maillacheruvu & McDuff, 2014). Effective diabetic check-ups are necessary to manage diabetes and diabetic complications, but this requires health care professionals who are not overworked, a sufficient availability of medical resources, and diabetic awareness and education to both undiagnosed and diagnosed diabetics — all of which are significantly resource intensive in an already resource-limited health care system. Since the management of diabetes in South Africa operates within a complex and burdened public health care system, it is, therefore, necessary to consider diabetic health care in South Africa from a holistic system's perspective, constituting dynamic interactions. Thus, this paper utilised system dynamics to explore the management of diabetes and diabetic complications in South Africa, with specific focus on type 2 diabetics.

METHOD

System dynamics is a simulation method first developed in the 1950s by Jay Forrester, who used the laws of physics to examine and characterise the dynamics of economic, as well as social structures

(Sterman J. , 2000). System dynamics has a wide application, including the health sector (Mielczarek & Uziałko-Mydlikowska, 2012) and in supporting public heath policy (Mabry, et al., 2010). It has also specially been utilised to understand diabetics population dynamics in the USA (Jones, et al., 2006). To the best knowlegde of the authors, there is, however, limited knowledge regarding system dyamics-based reseach on diabetes in South Africa.

Dynamic hypothesis

The dynamic hypothesis for the management of diabetes in South Africa, by improving the effectiveness of diabetic check-ups, is shown the causal loop diagram (CLD) in Figure 8-1. The CLD consists four feedback loops with three reinforcing loops and one balancing loop, namely the Diabetic Check-up Management loop (R1), the Diabetic Awareness by Doctors loop (R2), the Resource Availability loop (R3), and the Diabetic Awareness by Department of Public Health loop (B1).

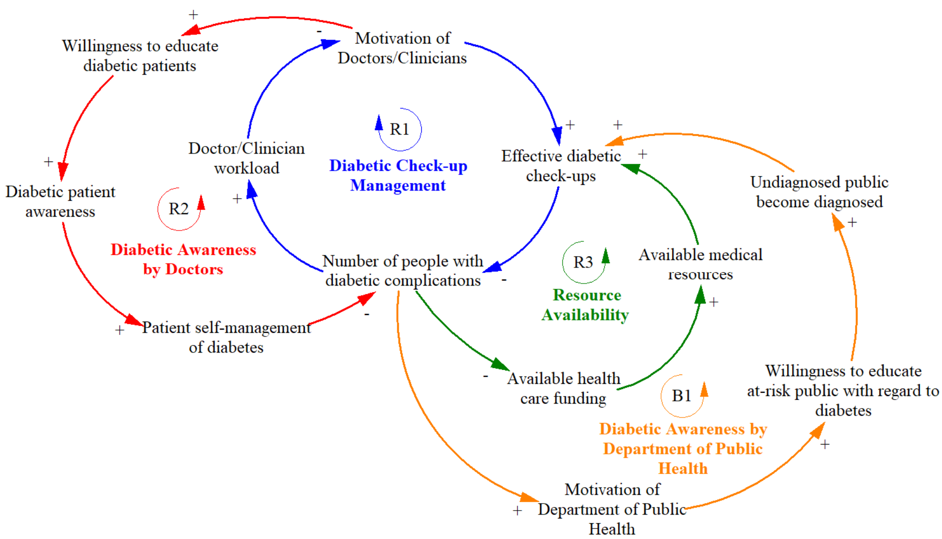

Figure 8-5: Overall Management of Diabetes in South Africa CLD

The Diabetic Check-up Management feedback loop (R1) demonstrates the effect of the workload on a health care professional's motivation to perform effective check-ups, which, in turn, reduces the number of diabetic complications. Similarly, the motivation of the doctors in the Diabetic Awareness by Doctors feedback loop (R2) increases the education and diabetic awareness supplied by doctors, which ultimately increases patient self-management and reduces the number of diabetic complications. In the Resource Availability feedback loop (R3), it may be observed that as diabetic complications decrease, the availability of medical resources increases, which leads to more effective diabetic check-ups. Finally, the Diabetic Awareness by Department of Public Health feedback loop (B1) shows how a decrease in the number of diabetic complications can lead to a decreased motivation of the Department of Public Health to educate the public that are at risk of developing diabetes, which leads to less undiagnosed diabetics, thus decreasing the diagnoses rate. This results in less effective diabetic check-ups and an increase in the number of people with diabetic complications.

Stock and Flow Model

For the purpose of this paper, which is work in progress, the preliminary stock and flow model provides the diabetic population dynamics in South Africa, which will enable the exploration of the four dynamic hypothesis. The model constitutes four stocks, as shown in Figure 8-2, namely: Number of undiagnosed diabetics without complications, Number of undiagnosed diabetics with complications, Number of diagnosed diabetics without complications, and Number of diagnosed diabetics with complications.

Scenario definition

Five scenarios were developed for analysis and evaluation against the baseline results of the model, and are presented in Table 8-1.

Table 8-3: Scenario definition

Scenario	**Description**
Baseline	
Education to undiagnosed	This entails increasing the current education to the undiagnosed diabetics by a factor of 5 from 2019 onwards
Education to diagnosed	This entails increasing the current education to the diagnosed diabetics by a factor of 5 from 2019 onwards
Motivation of doctor	This entails increasing the motivation of the doctors by a factor of 5 from 2019 onwards
Availability of resources	This entails increasing the availability of resources by a factor of 1.5

50 percent	(50% more resources available) from 2019 onwards
Availability of resources 100 percent	This entails increasing the availability of resources by a factor of 2 (100% more resources available) from 2019 onwards

PRELIMINARY RESULTS

Baseline results

The effectiveness of the diabetic check-ups are key in improving the management of diabetes and preventing diabetic complications in South Africa. The baseline results show that the total number of diagnosed and undiagnosed diabetics with complications continues to increase over the simulation period (See Figure 8-3).

Scenario analysis

In the *Education to undiagnosed* scenario, the *education to undiagnosed* variable is increased by a factor of 5 from 2019. The results (see Figure 8-4 and Figure 8-5) shows small effect on the number of diabetic population reduction relative to the baseline. Similarly, insignificant effect is observed in the *education to diagnosed* and the *motivation to doctor* scenarios. Only the a*vailability of resources 50 percent* and a*vailability of resources 100 percent* scenarios show a significant reduction in the number of diagnosed and undiagnosed diabetic population with complications.

From the scenario results, it is postulated that an increase in the medial resource availability for public health care facilities by at least 50% can improve the effectiveness of diabetic check-ups in the management of diabetes and diabetic complications, as opposed increasing the availability of resources by 100%, which only shows improvement in reducing the number of diabetic complications for a small portion of the simulation run, whilst being cost-intensive. Increasing the current education to the diagnosed diabetics, and undiagnosed diabetics, or the motivation to the doctors seem not to improve the effectiveness of diabetic check-ups.

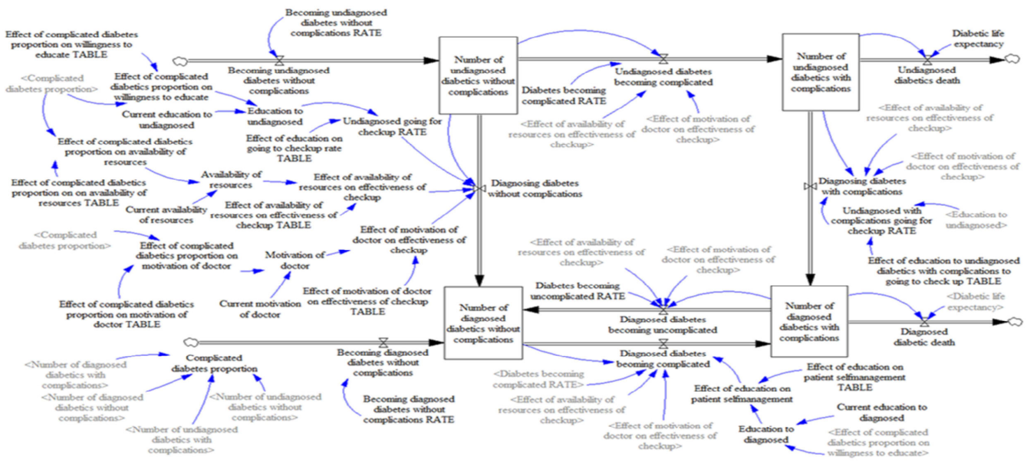

Figure 8-6: Stock and flow model

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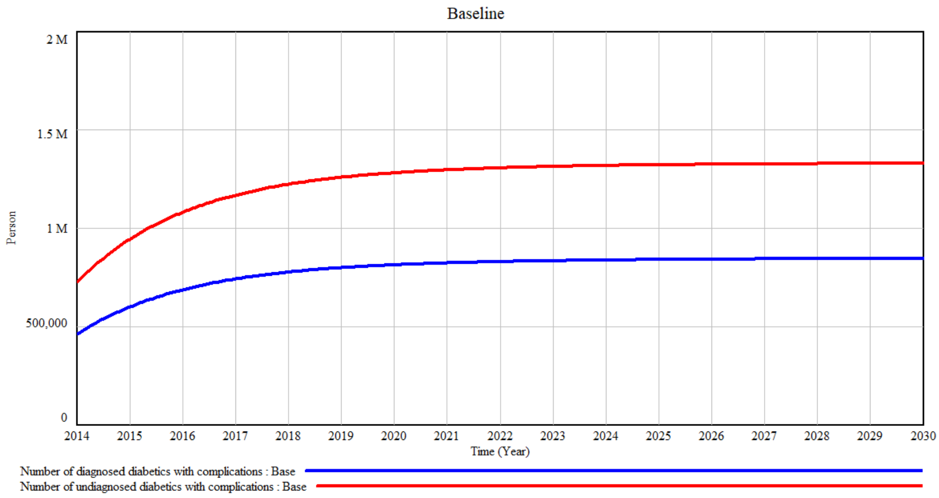

Figure 8-7: Baseline results

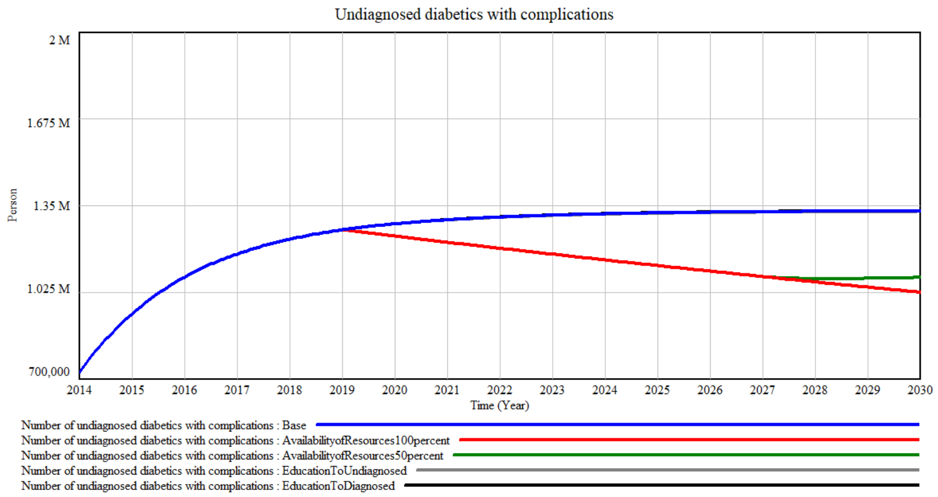

Figure 8-8: Undiagnosed with complications population scenario results

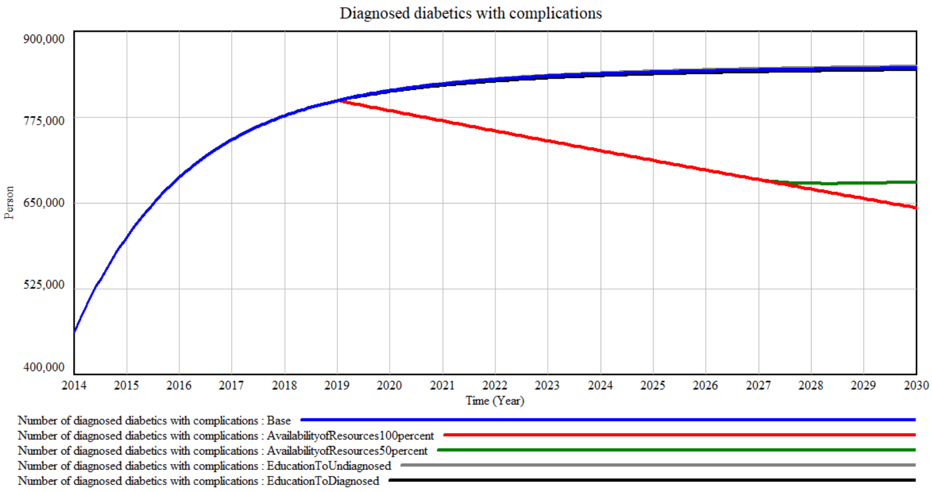

Figure 8-9: Diagnosed population with complications scenario results

CONCLUSIONS

The increasing prevalence of diabetes in South Africa is a critical concern. It is, therefore, necessary to consider the management of diabetes in South Africa from a holistic systems perspective. System Dynamics was considered as an appropriate method to accurately capture the relevant dynamics involved in the complex management of diabetics and diabetic complications in the South Africa heath care system. The *Availability of resources 50 percent* scenario was, however, identified as the most effective scenario for decreasing the number of diabetic complications, while still remaining cost-effective. The results presented are preliminary and the model is a work in progress to capture all the feedback loops described in the causal loop diagram.

ACKNOWLEDGMENTS

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